Deliverable D1.7 Details of the proof of concept data sharing solution

Spectrum sandbox project Work Package 1 deliverables

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

Real Wireless Ltd
PO Box 2218
Pulborough
West Sussex
RH20 4XB
United Kingdom

t +44 207 117 8514
f +44 808 280 0142
e info@real-wireless.com
w real-wireless.com
real-wireless

Issued to: DSIT **Issue date:** March 2025 **Version:** 2.0

realwireless.
independent telecoms experts

Version control

Item	Description
Source	Real Wireless
Client	DSIT
Report title	Deliverable D1.7 Details of the proof of concept data sharing solution
Subtitle	Spectrum sandbox project Work Package 1 deliverables
Issue date	March 2025
Document status	Final report
Comments	

Version	Date	Comment
1.0	23/12/2024	Interim version Issued to DSIT
2.0	08/03/2025	Final version Issued to DSIT

Document management	Date	Name	Position
Document prepared	01/03/2025	Aleksandar Damnjanovic, George Tsirtsis, Luigi Ardito Gurdeep Singh, Dr. Charles Turyagyenda, Joe Butler	Project Team, Qualcomm Project Team, Digital Catapult
Document reviewed	08/03/2025	Dr. Abhaya Sumanasena Simon Fletcher	Project Manager, Real Wireless Project Director, Real Wireless

realwireless.
independent telecoms experts

About Real Wireless

Real Wireless is the world's leading independent wireless advisory firm. Its network of experts includes engineers, physicists, economists, security advisors, business strategists and deployment specialists. Real Wireless clients benefit from a comprehensive portfolio of specialists and custom tools that analyse radio network performance, techno-economic impact and the business model implications of wireless systems. With this unmatched resource Real Wireless is able to advise the industry and all user groups, spanning businesses to governments, mobile operators, regulators and technology companies on every aspect of wireless technology.

Real Wireless has applied this unique range of technical and strategic expertise to some of the UK's biggest wireless infrastructure projects – from major stadium connectivity to shopping malls to transport systems — and has worked with operators, vendors and regulators on all forms of wireless connectivity. It has also advised governments and the European Union on the technical, social and economic implications of communications policy.

Real Wireless experts help clients to understand, select and deploy technology according to need; we deliver truly independent advice as we are not affiliated with any association, company or proprietary standard. That is why, with 5G on the horizon, Real Wireless is best placed to guide and advise businesses on the choices and opportunities next generation communications systems will bring.

For details contact us at:

e info@real-wireless.com

w www.real-wireless.com

real-wireless

Copyright ©2025 Real Wireless Limited. All rights reserved. Registered in England & Wales No. 6016945

realwireless
independent telecoms experts

Contents

1. Introduction 2
1.1 The PoC data sharing solution concepts under investigation 3

2. Technology pair 1 – Wi-Fi and mobile in the upper 6 GHz band 4
2.1 Derivation of Interference metric 4
2.2 Potential for sharing of usage and interference data for regulatory purposes 5
2.2.1 How would this interference metric be used by Ofcom for regulatory purposes? 5
2.2.2 Potential benefits of using the selected interference metric 5
2.2.3 Associated challenges 6
2.2.4 Recommendations for the future operation of such systems. 6
2.3 Visualisation techniques 6
2.4 Details of the PoC demonstration 7

3. Technology pair 2 - Independently operated private networks in the upper n77 band 8
3.1 Derivation of Interference metric 8
3.2 Our approach to deriving an interference metric 9
3.2.1 Interference Impact Metric (IIM) Framework 9
3.2.2 IIM for private 5G networks 10
3.2.3 IIM derivation from the measurement campaigns results 11
3.3 PoC data sharing solution 16
3.3.1 Commonly used approaches on spectrum data sharing and the status quo 16
3.3.2 Differences in data sharing approaches between the two papers 17
3.3.3 Proposed data sharing solution 18
3.3.4 Potential benefits of using the selected interference metric 19
3.3.5 Details of the experiments to derive trade-offs between raw data and averaging to derive a sensible volume of data 20
3.3.6 Associated challenges 20
3.4 Potential for sharing of usage and interference data for regulatory purposes 21
3.4.1 Proposed shared access licensing mechanism approach 21
3.4.2 Performance requirements for 5G applications 23
3.4.3 Practical Considerations for Requiring Performance Metrics in the Licensing Process 25
3.5 Visualisation techniques 26
3.6 Details of the PoC demonstration 29

4. Summary 32

Appendix A Acronyms 33

References 35

realwireless.
independent telecoms experts

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.

Each work package consists of a number of deliverables, each focusing on a different aspect of the project.

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

This report, D1.7, is an R&D report detailing the Proof of Concept (PoC) data sharing solution and explains how data may be shared with Ofcom to make necessary authorisation decisions. In D1.6, we demonstrated a PoC of key aspects of the proposed data-sharing solutions.

All deliverables from WP1 and their due dates are listed in **Table 1**.

Table 1: Summary of WP1 deliverables

Deliverable	Description	Due deliverable by
D1.1	Request and approval in principle from Ofcom for necessary authorisations to cover the duration of the project	Completed
I1.8	Format for archive and data agreed	Completed
D1.2	Develop R&D Report on design of sharing solutions, design rationale & expected performance	Completed
D1.3	R&D report detailing the measurement and data sharing solutions to be demonstrated in the final deliverable proof of concept.	Completed
D1.4	Develop a test plan, setting out system details, test conditions, spectrum parameters, & performance assessment approach	Completed
I1.5	Develop a preliminary test report of findings comparing system performance under conventional operation and more intensive spectrum sharing	Completed
D1.5	Develop a test report of findings comparing system performance under conventional operation and more intensive spectrum sharing	Completed
I1.7	Deliverable I1.7 Details of the proof of concept data sharing solution (Interim report)	Completed
D1.6	Report and proof of concept demonstration on potential for sharing of usage and interference data for regulatory purposes,	Completed

D1.7	**Report and interference data, setting out the potential benefits, associated challenges, and recommendations, including visualisation**	**Week 48**
D1.8	Archive of measurement and performance data captured during testing.	Completed
D1.9	Insights: Conclusions against objectives and relevant items of the Study questions, next steps. This report compares system performance under conventional operation and more intensive spectrum sharing, indicating how these field trials help develop an intensive spectrum-sharing solution.	Week 48

1.1 The PoC data sharing solution concepts under investigation

The objective of the PoC was to illustrate a data sharing solution that assesses future opportunities for ongoing data exchange regarding operations and performance with Ofcom. It enables spectrum users to share operational data with Ofcom. The shared data could facilitate Ofcom's operational spectrum assurance and compliance activities, such as identifying and addressing harmful interference, inform future improvements in spectrum management methods and the efficiency of spectrum use by incorporating real-world data in spectrum authorisations. Tracking interference, understanding utilisation, and analysing the propagation environment will ultimately lead to better-informed authorisations. In this report, we explain our vision for a PoC data sharing solution and, through appropriate PoC and prototyping activities, establish proof points for the feasibility of the solution using common standardised file transfer Application Programming Interfaces (APIs) with appropriate security and authentication mechanisms.

The PoC is expected to include a functional stub for the regulatory end of the interface, allowing demonstration of the end-to-end concept without actual integration with Ofcom. Consideration should be given to the following requirements:

- Identifying the most relevant metrics from each layer of the Open Systems Interconnection (OSI) stack, and determining the extent to which each metric is technology-specific or technology-neutral.
- Algorithms and pre-processing techniques should be developed to produce aggregate metrics from raw data, enhancing insight while reducing data volumes, such as identifying technologies from received waveforms and extracting performance statistics.
- The practicality of data provision should be evaluated in light of existing and future system capabilities to avoid imposing onerous costs.
- Arrangements for data sharing, including format, frequency, timeliness, and technical operation, should be defined.
    - The potential for standardised APIs, such as an “interference API” for real-time reporting of interference incidents and a “utilisation API” for real-time reporting of utilisation metrics, should be explored to facilitate prompt regulatory action and dynamic spectrum assignment.
- Challenges such as security, confidentiality, accuracy, calibration, and data volumes should be addressed.

Additionally, opportunities for regulators to derive greater value by aggregating and processing data from multiple sources, thereby gaining improved insights into interference sources, radio environments, and spectrum utilisation, should be considered.

Finally, visualisation techniques should be developed to showcase the insights derived from the data.

The following sections present the data sharing solutions from which PoCs shall evidence feasibility for the two technology pairs under assessment in the Real Wireless-led spectrum sandbox project:

1. Technology pair 1 - Wi-Fi and mobile sharing in the upper 6 GHz band[1]
2. Technology pair 2 - Independently operated private networks sharing in the upper n77 band[2]

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

The PoC demonstrates the suitability of cross technology signalling for data sharing, using the IEEE 802.11bc framework. Cross-technology signalling consists of IEEE 802.11bc messages, transmitted by 5G and received by a Wi-Fi Access Point (AP) as illustrated in Figure 1.

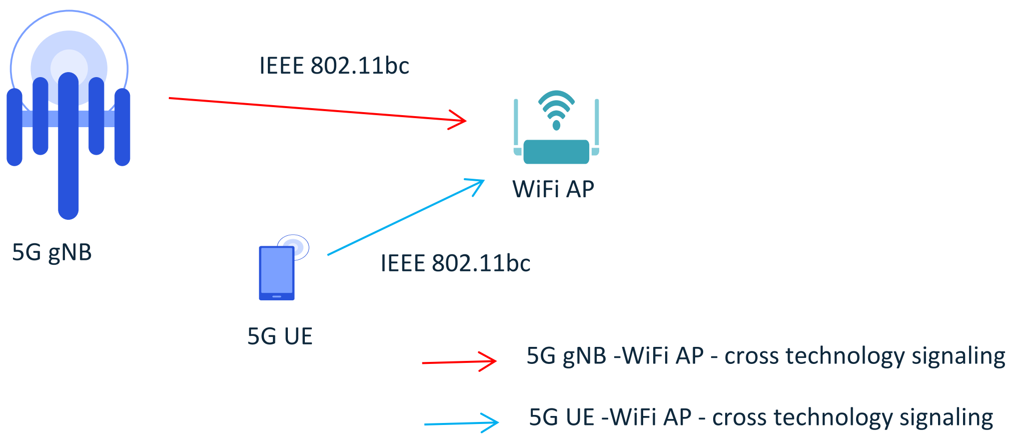

Figure 1: Utilising IEEE 802.11bc for cross-technology signalling.

The IEEE 802.11bc framework allows the content of the cross-technology signalling messages to be forwarded to the destination address. The content of the cross-technology signalling is considered Higher Layer Payload (HLP). The length of the message is flexible and can be customised for this use case.

2.1 Derivation of Interference metric

A simple metric that can accurately qualify interference conditions when two different technologies share spectrum can be a valuable tool to determine whether spectrum can be shared between two services. A simple method that processes “raw” data and produces aggregate metrics before such data can be shared is desired, so that the load towards the destination servers is minimised, per IEEE 802.11bc standard, the Enhanced Broadcast Services (EBCS) proxy can be configured to limit the amount of data shared. Yet meaningful information related to the interference between two services is shared and the aggregated metric identifies a pair of nodes which may not be able to concurrently utilise the same resources.

The throughput, the associated Reference Signal Power (RSRP) and Received Signal Strength Indication (RSSI) values and the occurrences of the decoding cross-technology signalling messages represent “raw” metrics in this experiment. The “raw” metrics are collected for the isolated and the co-located shared

[1] Upper 6 G Hz band refers to 6425 to 7125 MHz

[2] Upper n77 band refer to 3.8 - 4.2 GHz

spectrum deployment and processed to generate aggregated throughput values. The throughput values for isolated and co-located shared spectrum deployments are compared and correlated with the occurrences of successful decoding of cross-technology signalling messages.

The sharing of instantaneous throughput values would not be practical, among other reasons, due to the large amount of data that would need to be transferred. Utilisation of IEEE 802.11bc framework limits potential sharing of data to cross technology signalling only. Since IEEE 802.11bc is a standard, no additional costs are required for developing a new solution for data sharing. IEEE 802.11bc can be leveraged as an “interference API” for reporting of any events including events that can be classified as interference “incident” events or for “utilisation” metrics.

2.2 Potential for sharing of usage and interference data for regulatory purposes

2.2.1 How would this interference metric be used by Ofcom for regulatory purposes?

If the mobile service always has priority over Wi-Fi, the reception of cross-technology signalling transmitted by an International Mobile Telecommunications (IMT) deployment, may be interpreted as a request for the Wi-Fi AP to vacate the channel. The rationale is that if cross-technology signalling is received by Wi-Fi, due to channel reciprocity, Wi-Fi transmissions are interfering with IMT. In this scenario, there is a possibility to adopt a self-regulating approach. If a self-regulating approach is adopted, sharing of data does not impact the resulting action, which would always be the same. In case of a conflict, only the Wi-Fi service is reduced. However, sharing of data as elaborated further in the paragraph below could still provide insights into inter-technology interference in case of overlapping spectrum use that may be valuable to the regulator.

If a cross-technology signalling message is shared and reported to an associated destination server, the regulator may gain more insight into interference between two services when the spectrum is concurrently utilised. As discussed in European Conference of Postal and Telecommunications Administrations (CEPT) Project Team 1 (PT 1), IEEE 802.11bc [1] the uplink (UL) frame with HLP can be utilised for cross-technology signalling. The development of a new API for data sharing will not be necessary. In this scenario, as illustrated in Figure 2, the message is first validated with an EBCS proxy, which is a logical entity that may be collocated with the Wi-Fi AP. Per 802.11bc standard, in addition to validating the message, the EBCS proxy may also, per configured policy, limit the frequency of forwarded messages to the destination server and/or the AP may provide measurement data in addition to the information contained in the HLP part of the cross-technology signalling message. In residential deployments, it is suitable to have one EBCS proxy for each AP, while in enterprise deployments multiple APs may be served by a single EBCS proxy.

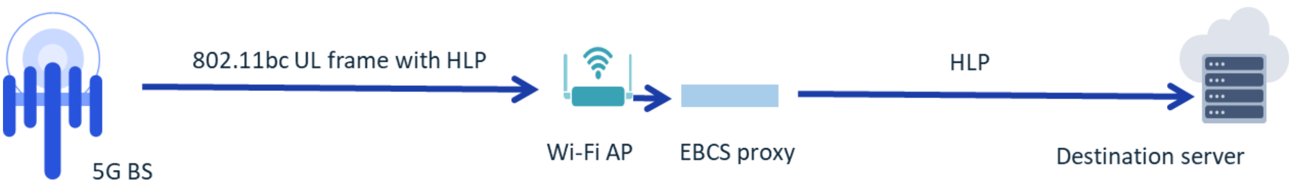

Figure 2: Sharing of data utilising IEEE 802.11bc.

2.2.2 Potential benefits of using the selected interference metric

Reception of cross-technology signalling messages by the Wi-Fi AP when transmitted by a 5G Base Station (BS) may be considered as an indication that interference between two technologies may occur which may lead to degradation of service. Due to channel reciprocity and the knowledge of the transmit power of the cross-technology signalling message by the 5G transmitter, the received signal strength of cross-technology signalling message at the Wi-Fi receiver can be leveraged to calculate the impact of Wi-Fi transmission to 5G as well. Strong interference between two systems would typically lead to significant service degradation for one or both technologies, therefore this signalling can be utilised as a simple metric that indicates harmful interference conditions.

2.2.3 Associated challenges

The main challenge with the cross-technology signalling based approach is to prove that service or throughput degradation can be correlated with the reception of cross-technology signalling. Only if it can be proven that cross-technology signalling can identify potential interference so that a mitigation action can be taken to avoid or minimise the service degradation, cross technology signalling can be adopted as an aggregate metric that substitutes all other collected Key Performance Indicators (KPIs) by 5G and Wi-Fi networks.

2.2.4 Recommendations for the future operation of such systems.

One of the benefits of leveraging the 802.11bc standard for cross-technology signalling is an opportunity to aggregate data from multiple Wi-Fi APs at the destination server. The aggregated data may be further analysed by Artificial Intelligence/Machine Learning (AI/ML) algorithms and potentially give more insights into the nature of interference environment, and determination of the relationship of the received signal quality for cross-technology signalling to service degradation, which may also be leveraged, when necessary, to deconflict use of resources.

2.3 Visualisation techniques

Utilisation of the 802.11bc standard allows the regulator to locate harmful interference conditions on a map. The location information further allows regulators to take proactive action and utilise AI/ML techniques to prevent interference and not simply react when interference conditions occur. Figure 3 illustrates how cross-technology signalling messages could be utilised to visualise locations where Wi-Fi should not be allowed to utilise the same time-frequency resources as IMT because it would potentially lead to service degradation for IMT or both technologies. The illustration in Figure 3 requires that the cross-technology signalling message, transmitted by IMT transmitter and received by Wi-Fi receiver includes the location of the receiver, the frequency resources utilised by IMT technology, and the time-stamp when the message is transmitted or received.

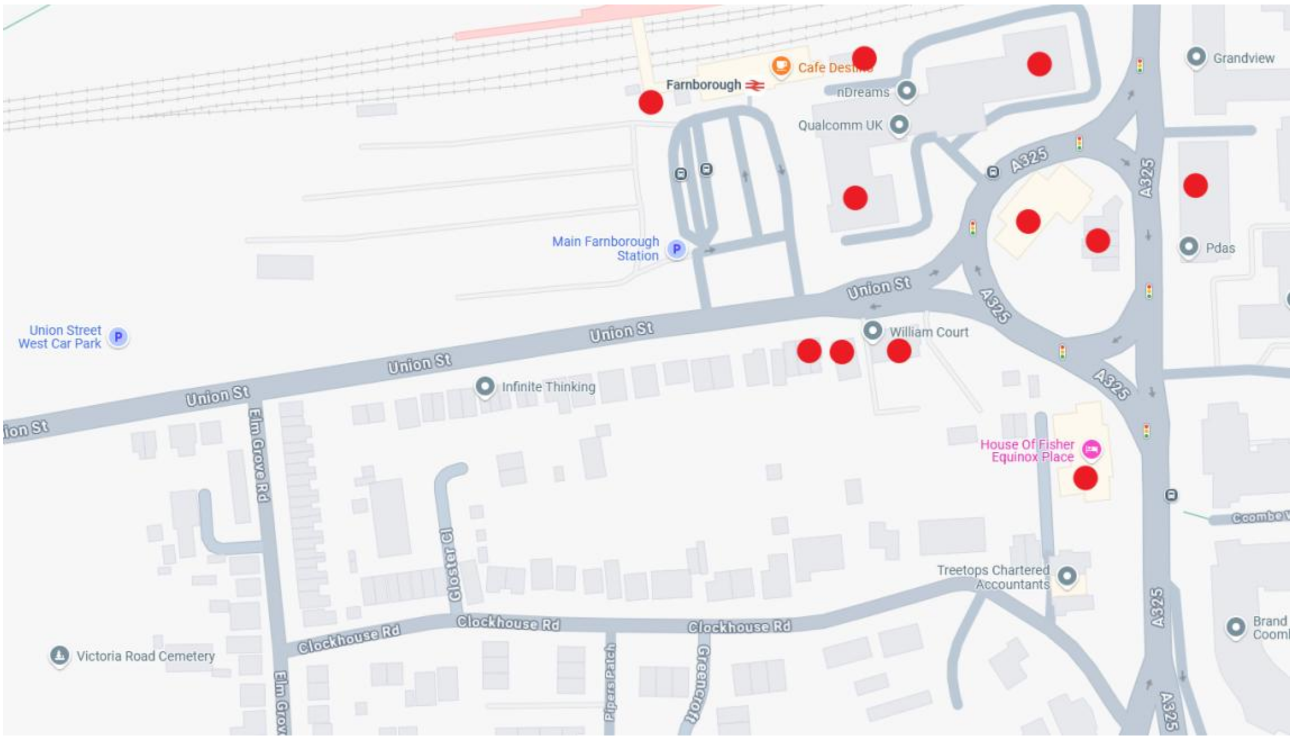

Figure 3: Illustration of Wi-Fi AP locations where cross-technology signalling was detected shown as red circle.

2.4 Details of the PoC demonstration

The proof of concept for the data sharing solution leveraging standardised IEEE 802.11bc framework was successfully demonstrated to a team of experts from DSIT and Ofcom on the 25th of February, 2025. During the presentation, we established key proof points validating the feasibility and effectiveness of the solution. The framework leverages broadcast data messages sent by 5G and received by Wi-Fi APs. The benefit of the broadcast messages is that the messages do not have to identify the interfering links one by one but rather can be done all at once, both by gNB and User Equipment (UE). IEEE 802.11bc is also a secure protocol. This means malicious attacks on Wi-Fi APs by broadcasting cross technology signalling messages would not cause the Wi-Fi AP to reselect the channel. Only the licensed operator would be authorised to configure its gNBs and associated UEs for these messages. The data is processed by the EBCS proxy, which is a logical entity within Wi-Fi AP that filters and forwards the data to a corresponding destination server using a standardise IP protocol. The destination server can store and process data of interest and be managed by Ofcom.

The PoC demo evaluated the correlation between the reception of cross-technology signalling by a Wi-Fi AP when transmitted by 5G and potentially shared with a server managed by Ofcom, and service degradation of both technologies. If the degradation of KPIs for both (or at least one) technologies is observed when cross-technology signalling is received, this data is considered useful for the purpose of enabling more intense use of spectrum. In addition, if KPIs of interest are not meaningfully impacted when cross-technology signalling is not received, the conclusion can be reached that intense use of spectrum is feasible for those scenarios. If the cross-technology signalling is not received, but meaningful impact on KPIs is observed, then one can conclude that use of cross-technology signalling as shown in the demo, cannot be utilised to guarantee that inter-technology interference does not lead to service degradation. In addition, the PoC demonstration showed that it is feasible for a regular 5G base station without Wi-Fi chip to transmit cross technology signalling.

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

In deliverable D1.3, we presented the methodology for developing a PoC data-sharing solution and identified the key requirements and considerations for developing such a solution.

This report presents our vision for a data-sharing solution and established proof points for the feasibility of the solution using common standardised file transfer APIs with appropriate security and authentication mechanisms. We used data collected during the sandbox field trials to develop the proposed PoC data sharing solution.

3.1 Derivation of Interference metric

Based on the results from the measurement campaigns, including both benchmarking and interference tests, we derived and proposed an interference metric for Ofcom based on the correlation between Signal to Interference and Noise Ratio (SINR) and the performance measurements.

The interference metric is intended to provide insights into interference tolerance levels for 5G applications operating using the Shared Access Licence (SAL) framework. The goal was to support Ofcom in evaluating the feasibility of increased spectrum sharing within this framework.

The test plan execution was divided into four different phases to ensure consistent data collection and reliable comparisons between baseline and interference tests (Further details are provided in deliverable D1.4 Test plan).

1. **Phase 1 - Location Identification**: Test locations were identified based on Radio Frequency (RF) coverage criteria, ensuring diverse radio conditions. Geographical areas were surveyed, and locations were documented with Global Positioning System (GPS) coordinates and environmental notes.
2. **Phase 2 - Cell Edge Identification**: Cell edge test locations were selected by surveying areas without RF Signal coverage.
3. **Phase 3 - Baseline Measurements**: Baseline tests (Transmission Control Protocol (TCP), User Datagram Protocol (UDP), UL, DL) were conducted under controlled conditions, with only the Micro Site active and no interference from the Macro Site.
4. **Phase 4 - Interference Measurements**: Tests were repeated with both Macro and Micro sites radiating, exploring different power and frequency configurations to analyse interference effects.

The data collected from the measurement campaigns and the derived Interference metrics could be shared through a secure interface (**Figure 4**). Raw data from the measurements campaign was analysed and processed by a measurement translation engine that could be deployed at the Ofcom premises, operating in tandem with the Ofcom database to derive meaningful insights.

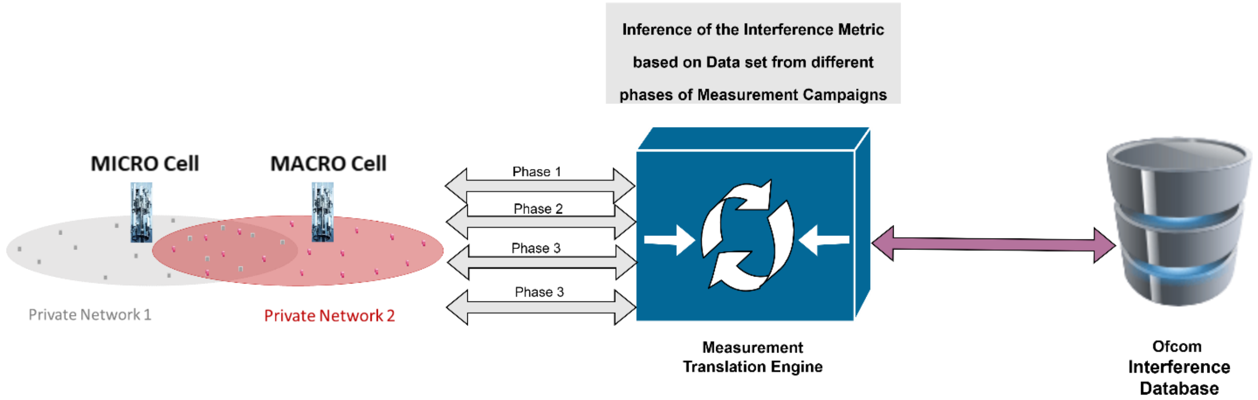

Figure 4: Interference Metric translation process

3.2 Our approach to deriving an interference metric

As the adoption of 5G technology accelerates, spectrum available under the SAL framework has emerged as a critical enabler for deploying private 5G networks, particularly in dense urban environments like London. By allowing multiple users to share spectrum, the SAL framework provides access to valuable spectrum for private networks to deploy a diverse set of applications, such as enhanced mobile broadband (eMBB) and industrial Internet of Things (IoT).

Some of the key characteristics considered for SAL in low and medium power deployments are as follows:

- **Dense deployment of private networks**: Co-located networks (e.g., enterprise, industrial, public venues) lead to higher inter-network interference.
- **Spectrum reuse**: SAL allows multiple entities to use the same frequency bands under non-exclusive arrangements, increasing the likelihood of interference.
- **Varied applications**: Private 5G networks cater to diverse use cases (e.g., IoT, low-latency automation, eMBB, etc.).
- **Urban challenges**: High user density, reflections, obstructions, and device diversity exacerbate interference.

However, the coexistence of overlapping networks in shared bands increases the likelihood of interference, which can degrade network performance and user experience. To identify the effects of interference, we propose a generalised Interference Impact Metric (IIM) tailored for SAL-based 5G deployments. The model leverages key performance indicators such as SINR, Layer 1 and application-level uplink and downlink throughput, and resource block utilisation to quantify the impact of interference on network performance. By integrating these parameters, the IIM provides a scalable, adaptable framework to evaluate and optimise interference management, ensuring efficient spectrum sharing.

3.2.1 Interference Impact Metric (IIM) Framework

The proposed IIM framework from our sandbox aims to address the unique challenges of spectrum sharing in dense urban environments. This IIM framework incorporates factors such as co-located network interference, urban propagation issues, and diverse use case requirements. The framework emphasises key parameters like SINR, throughput, and Physical Resource Block (PRB) utilisation while normalising these metrics to ensure comparability across networks. Use case-specific weights allow the model to prioritise different 5G applications and also cater to diverse private 5G deployment environments. This tailored approach ensures that the IIM remains flexible and relevant for monitoring and optimising SAL deployments.

The key metrics for 5G private networks environments include:

- **Signal quality**:
  - SINR (Physical Downlink Shared Channel (PDSCH) and Physical Uplink Shared Channel (PUSCH)): Measured interference at the physical layer.
  - Reference Signal Received Power (RSRP): Reflects signal strength and quality.
- **Throughput**:
  - L1 Throughput (DL and UL): Reflects the physical-layer capacity.
  - Application Throughput (DL and UL): Reflects real user experience at the Application Layer.
- **Spectrum efficiency**:
  - PRB Utilisation (DL and UL): Indicates how resources are allocated.
  - Modulation coding scheme (MCS): Captures modulation and coding under interference.
- **Error metrics**:
  - Block Error Rate (BLER): High BLER signals poor link reliability.

3.2.2 IIM for private 5G networks

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. Here's how the key components were determined:

- 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 [2] 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:

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

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 as mentioned in **Table 4**.

In the proposed framework the metrics for MCS and BLER were not considered as they have a direct impact on the PRB utilisation and throughput.

3.2.3 IIM derivation from the measurement campaigns results

In this section, we present the analysis and visualisation of the IIM derived from field measurements conducted during Baseline and Interference campaigns for both 100 MHz and 40 MHz Macro cell configurations. **Figure 5** and **Figure 6** present the IIM metric distribution across different radio conditions for TCP traffic in the downlink and uplink directions, respectively, while **Figure 7** and **Figure 8** illustrate the same for UDP traffic.

The IIM was calculated using a weighted approach, where w1 = 0.5, w2 = 0.4, w3 = 0.3, SINRIdeal =30 and PRBTotal = 273, representing the relative importance of key network parameters such as SINR, throughput efficiency, and resource block utilisation. By leveraging walk test data, this study provided a comparative assessment of network performance under varying interference conditions, offering insights into user performance, interference patterns, and overall network quality.

The provided results illustrate the IIM for TCP and UDP in downlink and uplink under three scenarios:

1. Baseline (no interference)
2. Interference with Macro cell having 100 MHz Bandwidth
3. Interference with Reduced Macro Cell Bandwidth

Since IIM measures the negative impact of interference on user performance, a higher IIM value means worse network conditions and a greater degradation of quality. The goal of mitigation strategies should be to lower IIM, thereby reducing interference impact and improving user experience.

Key observations from the TCP downlink results shows in **Figure 5**.

<u>**Baseline measurement campaign:**</u>

- IIM Values: Good (0.27), Fair (0.61), Poor (0.73)
- This represents an initial network condition with minimal interference, where the impact on user performance is relatively low.

<u>**Interference measurement campaign with Macro configured at 100 MHz bandwidth:**</u>

- IIM Values: Good (0.43), Fair (0.64), Poor (0.70)
- The increase in the "Good" category's IIM (from 0.27 to 0.43) and the "Fair" category's IIM (from 0.61 to 0.64) confirms that interference degrades user performance.

- However, a slight reduction in the "Poor" category's IIM (from 0.73 to 0.70) suggests that interference does not equally impact all radio conditions, possibly due to interference saturation.

Interference measurement campaign with Macro configured at 40 MHz bandwidth:

- IIM Values: Good (0.31), Fair (0.64), Poor (0.76)
- For "Good" category, IIM increases from 0.27 (Baseline) to 0.31 (Reduced bandwidth), showing a smaller degradation compared to full-bandwidth interference.
- For "Fair" category, IIM increases from 0.61 to 0.64, like the interference scenario, indicating bandwidth reduction does not significantly alleviate mid-range interference effects.
- For "Poor" category, IIM increases from 0.73 to 0.76, showing that reduced bandwidth does not mitigate interference in poor conditions and may worsen congestion effects

When comparing IIM trends between the baseline and interference with a macro cell having 100 MHz bandwidth, IIM slightly reduces in the Poor region (from 0.73 to 0.70), likely due to TCP congestion control distributing degradation across different radio conditions. However, overall IIM increases in the Fair and Good regions, indicating a general decline in performance.

Conversely, reducing the Macro cell bandwidth to 40 MHz leads to an increase in IIM in the Poor region (from 0.70 to 0.76), worsening network conditions for already degraded users due to fewer available resources and higher spectral efficiency demands, resulting in increased TCP retransmissions. Meanwhile, the Good category sees a slight improvement (from 0.43 to 0.31), suggesting that bandwidth reduction helps mitigate interference for stronger connections while severely impacting users in weaker radio conditions.

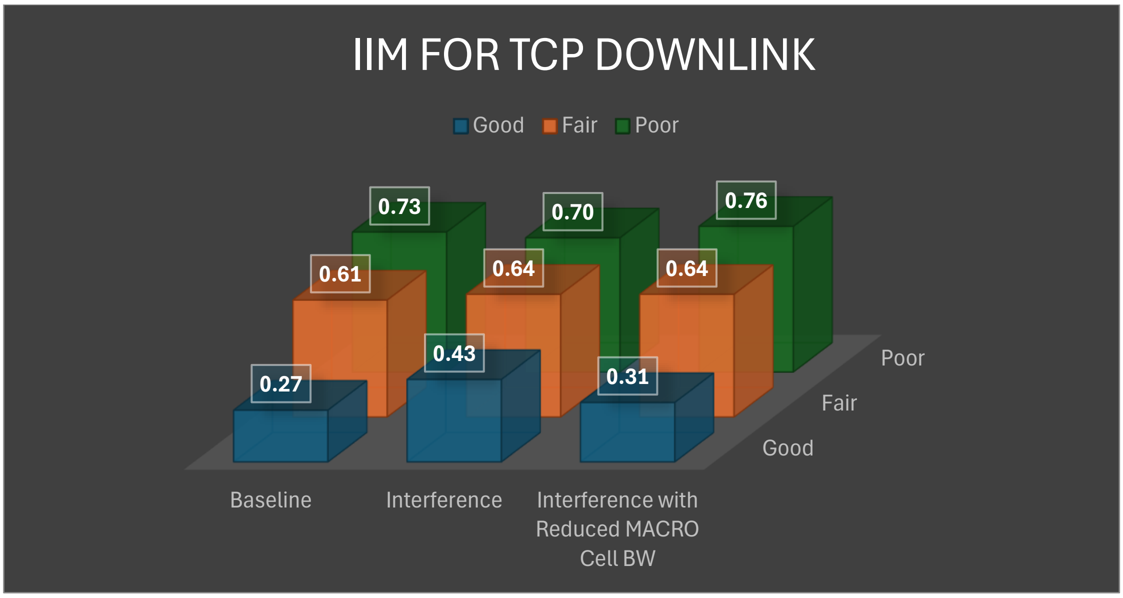

Figure 5: IIM for TCP Downlink for different Radio conditions

Key observations from the TCP uplink results shows in **Figure 6** and discuss below:

- Baseline to Interference:
    - The IIM values increase in all three regions (Good, Fair, Poor) when interference is introduced, showing a negative impact on TCP uplink performance.

    - The most significant increase occurs in the Poor region, where IIM jumps from 0.75 to 0.80, indicating severe degradation under interference.
- Effect of bandwidth Reduction:
    - **Good Region**: IIM drops from 0.41 to 0.21, showing that bandwidth adaptation improves performance.
    - **Fair Region**: IIM remains almost unchanged (0.69 to 0.70), suggesting a neutral effect of bandwidth adaptation in moderate conditions.
    - **Poor Region**: IIM slightly decreases from 0.80 to 0.76, but remains high, indicating that bandwidth adaptation does not fully mitigate interference in weak radio conditions.

In TCP uplink, the impact of interference is pronounced due to TCP's inherent congestion control mechanism, which misinterprets packet losses caused by interference as network congestion. This leads to unnecessary retransmissions, increased queuing delays, and reduced throughput, particularly in the Poor region where signal quality is already compromised. Bandwidth adaptation helps mitigate interference effects in the Good and Fair regions by reducing spectral contention and improving transmission stability. However, in the Poor region, the improvement remains limited as reduced bandwidth restricts resource allocation flexibility, and the low SINR levels persist despite bandwidth reduction. This indicates that while bandwidth adaptation is an effective mitigation strategy for moderate interference levels, additional measures such as power control and advanced interference cancellation techniques are necessary to enhance TCP uplink performance in highly degraded radio conditions.

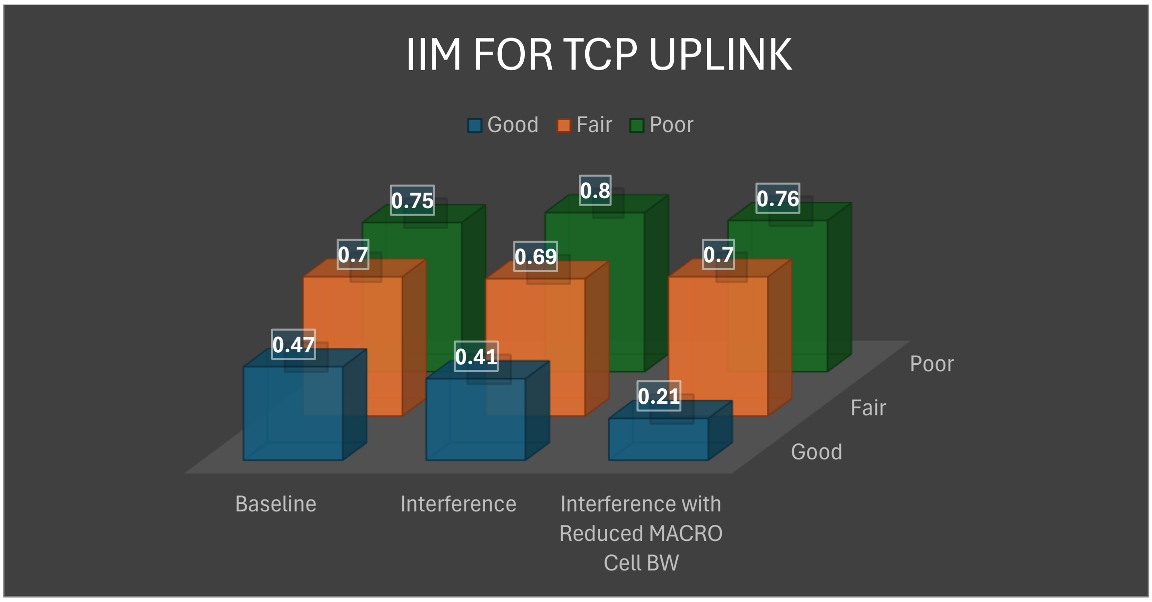

Figure 6: IIM for TCP Uplink for different Radio conditions

Key observations from the UDP downlink results as shown in **Figure 7**.

<u>Baseline measurement campaign:</u>

- IIM Values: Good (0.35), Fair (0.59), Poor (0.74)
- Like TCP, the initial condition shows minimal interference.

<u>Interference measurement campaign with Macro configured with 100 MHz bandwidth:</u>

- IIM Values: Good (0.36), Fair (0.64), Poor (0.72)
- For "Good" category, IIM increases from 0.35 (Baseline) to 0.36 (Interference), indicating minimal degradation due to interference.
- For "Fair" category, IIM increases from 0.59 to 0.64, showing moderate impact on mid-range network conditions.
- For "Poor" category, IIM slightly decreases from 0.74 to 0.72, suggesting interference saturation effects, where further interference does not significantly worsen performance.

Slight increase in interference impact in Good and Fair categories, meaning that interference negatively affects UDP performance but not as severely as TCP.

<u>Interference measurement campaign with Macro configured with 40 MHz bandwidth:</u>

- IIM Values: Good (0.33), Fair (0.68), Poor (0.71)
- For "Good" category, IIM decreases slightly from 0.35 (Baseline) to 0.33 (Reduced bandwidth), indicating slight improvement under reduced bandwidth.
- For "Fair" category, IIM increases from 0.59 to 0.68, showing that reducing bandwidth may worsen performance in mid-range conditions due to increased spectral congestion.
- For "Poor" category, IIM decreases from 0.74 to 0.71, suggesting that in extreme interference scenarios, reduced bandwidth may help slightly mitigate the impact.

The comparison of UDP Downlink IIM between Baseline and Interference with 100 MHz bandwidth macro cell shows that the Fair region experiences the most degradation, with increased IIM indicating a moderate interference impact. In the Good region, there is minimal change, demonstrating UDP's resilience under strong signal conditions. The Poor region sees a slight decrease, likely due to interference saturation, where additional interference has a limited effect.

When comparing Baseline to Interference with reduced macro cell bandwidth, there is a slight improvement in the Good region, suggesting that reducing bandwidth helps mitigate interference in areas with strong signals. However, the Fair region sees higher IIM, indicating that bandwidth reduction may increase congestion effects. The Poor region shows only a marginal decrease, providing minor relief from interference in weak signal areas.

In the comparison between Interference impact caused by macro cells having 100 MHz bandwidth and 40 MHz bandwidth, the Good region improves slightly, suggesting some mitigation under reduced bandwidth. The Fair region worsens, indicating that reducing bandwidth does not always alleviate interference. The Poor region remains largely unchanged, reinforcing the idea that interference saturation limits further degradation.

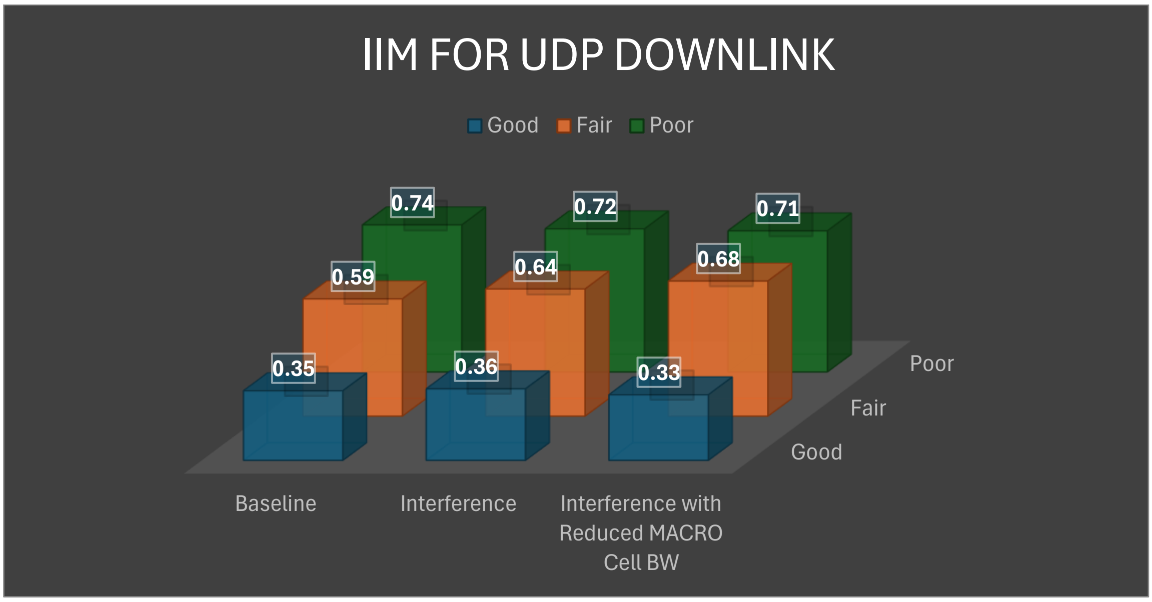

Figure 7: IIM for UDP Downlink for different Radio conditions

Key observations from the UDP uplink results shown in **Figure 8**.

Baseline to Interference:

- The IIM values increase across all regions with interference, confirming that UDP performance is impacted, though slightly less than TCP.
- The Poor region again experiences the highest impact, with IIM increasing from 0.76 to 0.80, indicating severe degradation.

Effect of bandwidth Reduction:

- Good Region: IIM drops from 0.49 to 0.36, showing that bandwidth adaptation effectively reduces interference.
- Fair Region: IIM remains almost unchanged (0.64 to 0.65), suggesting limited impact.
- Poor Region: IIM increases from 0.70 to 0.80, showing that bandwidth adaptation does not help users in weak radio conditions.

In the UDP uplink, interference significantly impacts performance due to the protocol's lack of congestion control and retransmission mechanisms, making it highly susceptible to packet loss. The IIM trends show increased interference effects in the Poor region, where high packet loss leads to severe degradation in user experience. Bandwidth adaptation helps mitigate interference in the Good and Fair regions by reducing spectral contention and improving link reliability. However, in the Poor region, the benefit is limited as reduced bandwidth constrains resource allocation, and the already weak signal conditions persist. **This suggests that while bandwidth adaptation can be a useful strategy for moderate interference, additional techniques like power control, adaptive modulation, and coding are required to enhance UDP uplink performance in highly degraded conditions.**

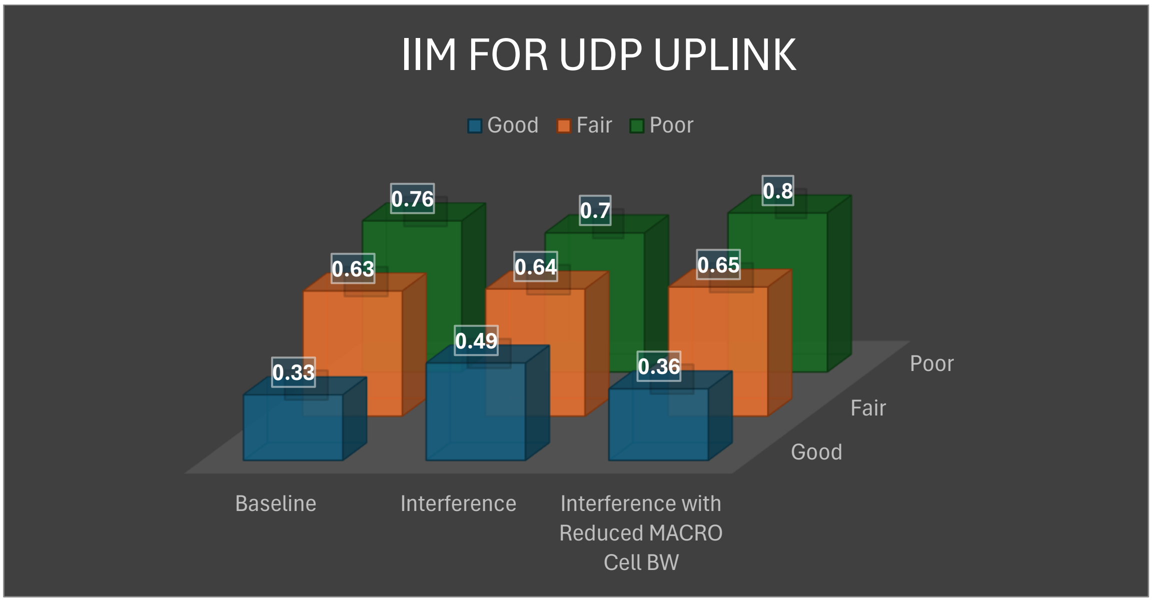

Figure 8: IIM for UDP Uplink for different Radio conditions

3.3 PoC data sharing solution

In this section, we present our analysis of how we share this data, i.e. IIM, with the regulator for onward decision-making. As the first step, we conduct research into commonly used approaches to spectrum data sharing.

3.3.1 Commonly used approaches on spectrum data sharing and the status quo

We explored various standardised approaches to define the data sharing solution, drawing on methodologies proposed by different Standards Development Organisations (SDOs), such as 3GPP. As part of this research, we considered two very different approaches detailed in [3] and [4] to inform the proposed data sharing solutions.

1. **Data sharing approach discussed in the Open Spectrum Data research publication** [3]: The growing complexity of RF environments requires scalable, collaborative, and standardised data-sharing models to enable efficient spectrum monitoring and utilisation. This generalised framework outlines a modular and adaptable approach for deploying and managing spectrum observatories, measurement systems, and open data-sharing platforms.

   Standardised frameworks enable the effective sharing and utilisation of collected spectrum data and employs the following techniques for efficient solutions.

   - **Dynamic spectrum access (DSA)**: The data-sharing framework supports dynamic spectrum-sharing paradigms, identifying underutilised frequencies and enabling efficient allocation through shared access models. These approaches are vital for emerging wireless technologies, including next-generation networks.
   - **Dataset design**: Open datasets often include detailed metadata (e.g., frequency range, resolution bandwidth, timestamps) to facilitate downstream analysis.
     - Data is structured with metadata describing frequency ranges, resolution bandwidths, timestamps, and geographical locations.

    - Standard file formats (e.g., Comma Separated Values (CSV), MATLAB) ensure ease of access and integration into existing tools for researchers and policymakers.
- **Global comparability**: By adhering to standardised measurement protocols and band plans, datasets from different regions or observatories can be directly compared, facilitating global analysis and harmonised regulatory decisions.

This generalised data-sharing model emphasises scalability, accessibility, and interoperability for spectrum monitoring. By leveraging standardised protocols and open-access datasets, the framework ensures that diverse stakeholders can effectively utilise spectrum resources. Its adaptability makes it an essential tool for future research, policy development, and technological innovation in RF spectrum management.

2. **Data sharing approach discussed in Electrosense: Open and Big Spectrum Data [4]** As RF spectrum usage becomes increasingly complex, scalable and accessible solutions for data sharing have become essential. Traditional spectrum monitoring systems often face limitations in scalability, application diversity, and cost-effectiveness. The proposed data-sharing model addresses these challenges through a collaborative, open-access framework that leverages modern technologies for secure and efficient spectrum monitoring.

- Open Spectrum data as a Service (OSDaaS) paradigm: The OSDaaS model provides a flexible framework for sharing spectrum data with multiple applications simultaneously. Unlike traditional "Infrastructure as a Service" approaches, OSDaaS ensures that data remains accessible to all stakeholders without conflicts, enabling historical data reanalysis and real-time applications. Data pipelines include Power Spectral Density (PSD) for general analysis and In-phase/Quadrature (IQ) components for more detailed studies, offering flexibility to meet diverse user requirements.
- The central approach to the model is a robust API that facilitates seamless access to spectrum data. The API supports both bulk and real-time data retrieval, offering aggregated data with functions like averaging and raw data for detailed analyses. This approach allows stakeholders to access pre-processed data as well as results from backend analytics, such as anomaly detection and modulation classification, thus enabling tailored applications without requiring extensive infrastructure.
- Security and privacy: The data-sharing model prioritises security and privacy through comprehensive mechanisms. Sensor registration ensures proper authentication, while data transmission is secured with encrypted channels. Data privacy is maintained by restricting raw IQ data access and by obfuscating sensor locations to protect user identities. These measures are crucial for ensuring trust and encouraging broader participation in spectrum monitoring initiatives.

The model encourages open participation by providing open-source frameworks and APIs, enabling stakeholders to develop custom applications and contribute to ongoing spectrum research.

3.3.2 Differences in data sharing approaches between the two papers

The two publications followed different approaches for data sharing and the major differences are listed in **Table 2**.

Table 2: Summary of comparison between the two data sharing approaches

Aspect	Electrosense: Open and Big Spectrum Data	Open Spectrum Data
Primary Focus	A crowdsourced approach for large-scale, open-access spectrum monitoring using low-cost sensors.	A centralised spectrum observatory model using advanced spectrum measurement equipment.
Deployment Strategy	Relies on widespread deployment of low-cost sensors (e.g., SDR and Raspberry Pi).	Focuses on a few geographically centralised, high-performance observatories.
Data Sharing Model	OSDaaS model, enabling multi-user simultaneous access.	Structured datasets designed for periodic sharing and integration into specific research workflows.
API and Flexibility	Offers an open API for real-time and bulk data retrieval; supports user-developed applications.	Provides datasets in structured file formats (e.g., CSV, MATLAB) with limited interactivity.
Scalability	Scalable through crowdsourcing and distributed sensor networks.	Limited to the scalability of centralised, high-performance observatories.
Security and Privacy	Implements data privacy controls such as location obfuscation and restricted IQ data access.	Primarily relies on localised, secure equipment without extensive user-driven access mechanisms.
Data Processing Architecture	Utilises a Lambda architecture [5] with batch, speed, and serving layers for real-time processing.	Centralised storage and processing with a predefined band plan for consistent data collection.
Collaboration and Governance	Open participation through crowdsourced contributions from volunteers and researchers.	Structured collaboration between a small group of institutions managing observatories.
Cost Efficiency	Designed for low-cost deployment using accessible hardware.	Relatively high-cost setup due to reliance on sophisticated measurement systems.

3.3.3 Proposed data sharing solution

To enable regulators to efficiently use data for authorisation purposes, existing data formats need to be generalised and standardised. This ensures compatibility, security, and comprehensibility across different platforms and stakeholders. The adopted data sharing solution technique uses the methodology defined under IEEE paper for Open spectrum data [3] and the data collected through the field measurement campaigns and send that data through a secure interface. We used message transfer Secure Copy Protocol (SCP) as this methodology uses a simplified mechanism of transferring the intended datasets between the user and the regulatory body. The adopted methodology enables a flexible deployment architecture with a central Ofcom database repository and adopts an industry wide acceptable approach for sharing data across multiple channels. The process involves the following steps:

- **Adopting common data sharing techniques:** The solution involves utilising standardised data sharing methodologies to ensure uniformity and ease of interpretation. Data collected through measurement campaigns can be processed and shared in widely accepted formats such as JSON, XML, or CSV, depending on the complexity and type of data. These formats support flexibility in structure while maintaining consistency in representation.
  - **Secure data transfer protocols:** Security is paramount in sharing sensitive data with regulators. Data transmission should occur through secure interfaces employing robust protocols. For instance, leveraging SCP for file-based transfers provides an additional layer of security through authenticated encryption mechanisms, ensuring safe and reliable data delivery.
- **Documentation and training**: Clear documentation on the data structure, transfer mechanisms, and interpretation guidelines are essential. Training programs for stakeholders on the use of generalised formats can facilitate smooth adoption and compliance.

By implementing these strategies, existing data formats can be effectively generalised, enabling regulators to utilise the data seamlessly for authorisation purposes. This approach not only ensures technical compatibility but also fosters transparency and trust among all stakeholders involved.

3.3.4 Potential benefits of using the selected interference metric

The IIM methodology offers several key benefits, particularly in the context of managing interference in 5G networks operating under shared spectrum licensing frameworks. These benefits can be categorised into technical, operational, and user-experience aspects:

1. **Technical benefits**
   - Quantifiable interference assessment: The IIM provides a measurable and unified way to evaluate the impact of interference on network performance, using key metrics like SINR and throughput. This quantitative approach aids in network optimisation.
   - Scalability for diverse use cases: The methodology accommodates various 5G use cases such as eMBB, ultra-reliable low-latency communication (URLLC), and massive IoT by adjusting weight factors and thresholds.
2. **Operational Benefits**
   - Efficient resource utilisation: Network operators can optimise resource allocation (e.g., PRBs, MCS selection) based on IIM scores, leading to more efficient utilisation of network capacity.
   - Simplified monitoring and decision-making: The IIM integrates multiple performance parameters into a single metric, simplifying the monitoring process for network operators and enabling data-driven decisions for interference mitigation.
   - Support for network planning: IIM-based maps provide insights into interference trends in diverse deployment scenarios, aiding in strategic planning for infrastructure deployment, such as small cells
3. **Benefits to User Experience**
   - Improved performance: By aligning interference measurements with application throughput, the IIM ensures that user-centric performance metrics are prioritised, improving overall service quality for end users.

- Fair access in shared spectrum: In shared access scenarios, the IIM helps maintain equitable performance across users and applications, reducing the likelihood of service degradation due to interference.

3.3.5 Details of the experiments to derive trade-offs between raw data and averaging to derive a sensible volume of data

In the conducted experiments, low-level information based on 3GPP-defined 5G protocols was gathered during the measurement campaigns. These campaigns were designed to capture granular data points such as signal strength, throughput, and network performance indicators across various conditions and locations. The raw data was collected using advanced test and measurement tools, such as Nemo Outdoor, a comprehensive field measurement solution known for its precision and versatility in network data acquisition.

The measurement tools were configured to collect extensive low-level protocol information directly from the user device. This included details on:

- Layer 1 and Layer 2 performance metrics.
- User equipment (UE) performance metrics under different scenarios.

The raw data collected during these campaigns was subsequently processed into a readable and structured format, such as CSV, Excel spreadsheets, using the processing capabilities of Nemo Outdoor tool. This step involved data parsing, cleaning, and organising to ensure that critical insights were easily interpretable and actionable.

To maintain the sanctity and authenticity of the measurement campaigns, both the raw and processed data were preserved and prepared for sharing with regulators. The raw data provides an unaltered baseline, ensuring transparency and allowing regulators to independently validate the findings. Meanwhile, the processed data offers a consolidated view, simplifying interpretation and aiding decision-making.

- Regulatory Compliance: Providing both raw and processed data ensures adherence to stringent regulatory requirements and facilitates authorisation processes.
- Traceability: The inclusion of raw data enables traceability, and fosters trust in the reported findings, as regulators can cross-check and audit the original measurements.
- Improved Analysis: The processed data format enhances usability, enabling regulators to analyse trends and patterns efficiently without the need for specialised tools.

By employing this dual-data sharing methodology, the measurement campaigns achieved a balance between providing exhaustive technical details and delivering actionable insights to regulators.

3.3.6 Associated challenges

While conducting measurement campaigns and sharing data for regulatory purposes, several challenges can arise at various stages of the process. These challenges include both technical and operational related issues.

1. **Data collection challenges**
    - Complexity of 5G protocols: Gathering low-level information based on 3GPP-defined 5G protocols requires specialised tools and expertise. The complexity of the protocols can lead to challenges in configuring the measurement equipment and capturing all relevant data points.

- Dynamic network conditions: 5G networks operate in dynamic environments with fluctuating parameters such as user density, mobility, and interference. Capturing consistent data across these varying conditions is challenging.

2. **Data processing challenges**
   - Volume of raw data: The sheer volume of raw data collected during measurement campaigns can be overwhelming, necessitating robust processing tools to clean, organise, and extract meaningful insights.
3. **Data sharing challenges**
   - Ensuring data integrity: Transmitting both raw and processed data to regulators while preserving its accuracy and authenticity requires secure, reliable transfer protocols.
4. **Operational challenges**
   - Resource Constraints: Conducting large-scale campaigns often demands significant human and technical resources, including field teams, advanced tools, and computational power.
   - Environmental factors: External conditions such as weather, geographic accessibility, or signal interference can impact the quality and reliability of data collection.

3.4 Potential for sharing of usage and interference data for regulatory purposes

This section emphasises the application of the IIM framework within Ofcom's licensing mechanism to evaluate the potential interference a new service may introduce into the spectrum environment. Integrating IIM into the SAL framework could improve spectrum management by offering a clearer insight into interference dynamics thus facilitating the efficient and timely deployment of new services and technologies.

3.4.1 Proposed shared access licensing mechanism approach

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 9** 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.

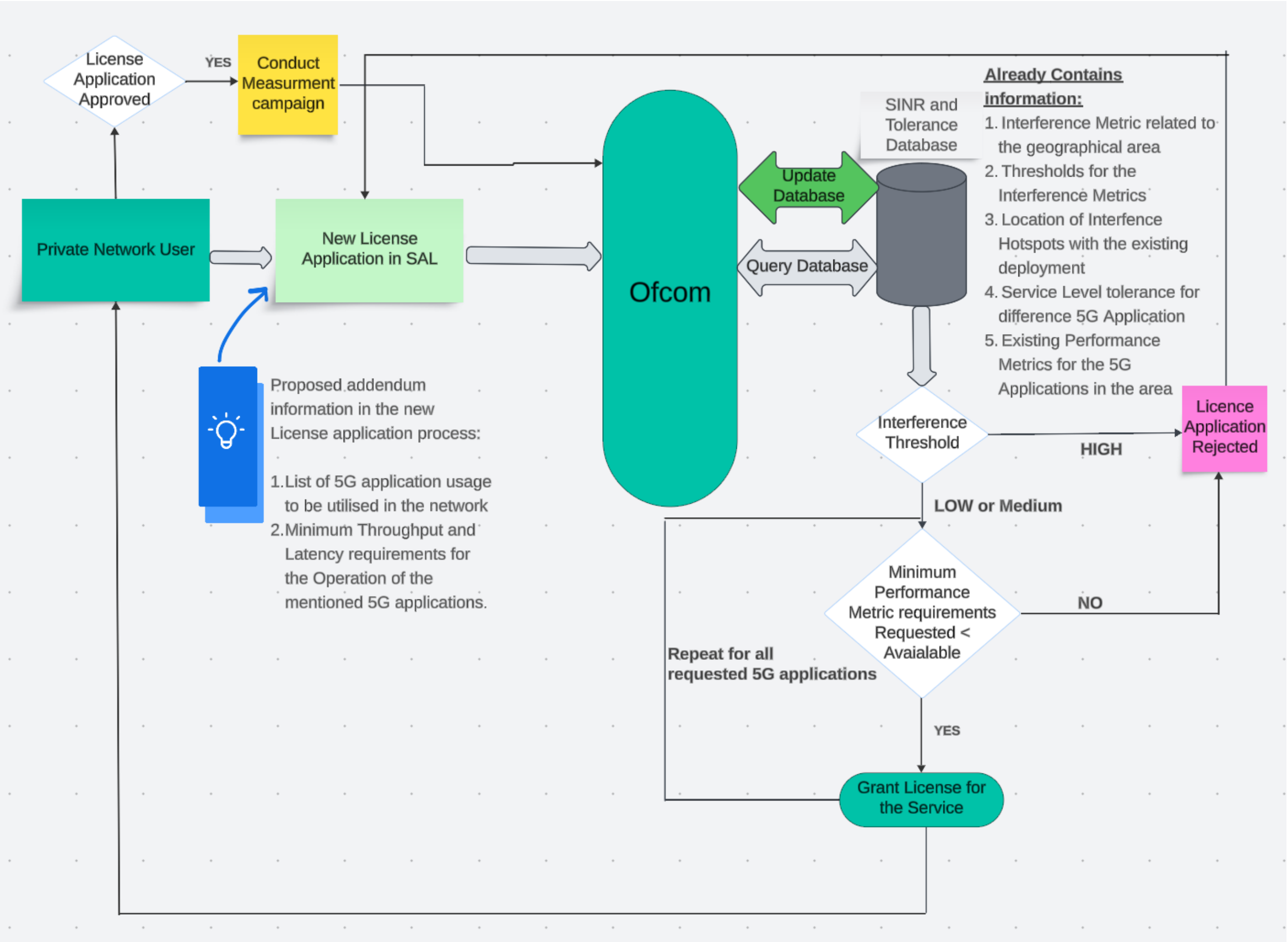

Figure 9: Shared access licence application process

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.

Key aspects of the application-agnostic licensing process:

1. **Uniform Evaluation Criteria**
    - The process does not differentiate between different types of 5G applications (e.g., industrial automation, IoT, AR/VR, or mission-critical communication).
    - Instead, all applications are assessed based on their minimum throughput, latency, and interference tolerance requirements.
2. **Database-Driven Interference Analysis**
    - Ofcom queries an IIM database, which contains IIM values and service level tolerances.

- The assessment is made based on whether the new deployment meets the interference constraints, independent of the application type.

3. **Threshold-Based Approval**
    - If the new deployment results in a high interference level, the application is rejected.
    - If interference remains low or medium, the system evaluates whether the requested performance metrics (throughput/latency) can be supported.

This ensures optimal network resource utilisation in overlapping private networks while maintaining user experience and service quality.

3.4.2 Performance requirements for 5G applications

Table 3 below provides a consolidated overview of the minimum performance requirements for various 5G applications across different use cases. It includes key parameters such as end-to-end latency, data rate, and reliability, which are critical for ensuring optimal service quality. Additionally, relevant references from 3GPP and European Telecommunications Standards Institute (ETSI) specifications are provided to offer a standardised perspective on these requirements. This information serves as a useful reference for understanding how 5G technology supports diverse applications, from voice and video communication to industrial automation and autonomous vehicles etc.

Table 3: 5G Minimum performance requirements

Application	End-to-End Latency	Data Rate	Reliability	Notes	Spec Reference
Voice over 5G (VoNR - Voice over NR)	≤ 100 ms	64–128 kbps	99.9%	Ensures smooth real-time voice communication	3GPP TS 22.261, Sec. 6.2.2
Video Calls / Conferencing	≤ 50 ms	1–10 Mbps	99.9%	Includes services like Zoom, Microsoft Teams, and FaceTime over 5G	3GPP TS 22.261, Sec. 6.2.2
Video Streaming (High Definition (HD)/4K/8K)	≤ 50 ms	3–50 Mbps	99.9%	Depends on resolution (HD = 3–5 Mbps, 4K = 15–25 Mbps, 8K = 50 Mbps+)	3GPP TS 22.261, Sec. 6.2.3
Online Gaming (Cloud Gaming - Augmented Reality (AR)/ Virtual Reality (VR)/ Extended Reality (XR))	≤ 10–20 ms (AR/VR: ≤ 5 ms)	10–50 Mbps	99.9%	Low latency is critical for real-time response in gaming	3GPP TS 22.261, Sec. 6.2.5
AR	≤ 5–20 ms	10–100 Mbps	99.9%	Used in applications like smart glasses, industrial AR, and retail AR	3GPP TS 22.261, Sec. 6.2.5
VR	≤ 5 ms	50–200 Mbps	99.999%	Needed for immersive VR experiences with minimal motion sickness	3GPP TS 22.261, Sec. 6.2.5

Industrial Automation (Smart Factories)	≤ 1–10 ms	1–10 Mbps	99.9999%	Supports robotic control, remote machinery, and automation	3GPP TS 22.261, Sec. 6.3.2
Autonomous Vehicles (V2X - Vehicle-to-Everything)	≤ 1–10 ms	10 Mbps – 1 Gbps	99.9999%	Includes vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I)	3GPP TS 22.186, Sec. 5.1
Remote Surgery (Telesurgery / Haptic Feedback)	≤ 1 ms	10 Mbps – 1 Gbps	99.9999%	Requires ultra-low latency for real-time medical operations.	3GPP TS 22.261, Sec. 6.3.4
Smart Grids (Energy Networks)	≤ 5–20 ms	100 kbps – 10 Mbps	99.999%	Used for power distribution and energy management.	3GPP TS 22.261, Sec. 6.3.3
Massive IoT (Massive Machine Type Communications (mMTC) - Smart Cities, Sensors)	N/A	10–100 kbps per device	99.99%	Supports millions of connected devices like smart meters and sensors	3GPP TS 22.261, Sec. 6.3.5
Drones (Unmanned Aerial Vehicle (UAV) Communication)	≤ 5–50 ms	10 Mbps – 100 Mbps	99.999%	Used for surveillance, delivery, and remote inspection	3GPP TS 22.261, Sec. 6.3.7
Emergency Services (Mission Critical Communications - MCX)	≤ 1–50 ms	1–100 Mbps	99.9999%	Includes public safety networks, disaster response, and push-to-talk	3GPP TS 22.261, Sec. 6.3.6
Cloud Storage & Data Transfers	N/A	10 Mbps – 1 Gbps	99.99%	Affects download/upload speed for cloud services like Google Drive	3GPP TS 22.261, Sec. 6.2.3
Professional Audio Production	≤ 0.75 ms	100 kbps – 5 Mbps	99.9999%	Used in live music festivals, musicals, and audio studios	ETSI TS 122 263, Sec. 6.2.1

The minimum performance requirements for various 5G applications aids the proposed changes in the license application process by defining the key parameter thresholds that must be considered when evaluating new private network licenses.

- **Table 3** provides a standardised reference for these requirements, ensuring that license applicants define performance expectations accurately.
- Ofcom can check if the requested performance metrics (latency, throughput, reliability) can be met based on:
  - Existing interference conditions
  - Available network resources
- Provides baseline service quality requirements for different 5G applications thus helping to assess if the current network conditions are sufficient to meet the requirements of the requested 5G applications.

- If the IIM threshold is low or medium, Ofcom further evaluates whether the requested minimum performance metrics are available. **Table 3** helps determine if the requested service levels align with realistic network conditions.

By incorporating the minimum performance requirements, the licensing process ensures that:

- Applicants define their service needs in a structured way.
- Ofcom can assess applications based on real-world network capabilities.
- Network performance expectations align with standardized 5G service levels.

3.4.3 Practical Considerations for Requiring Performance Metrics in the Licensing Process

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.

1. **Challenges in asking users for performance requirements**
    - 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.
2. **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.

While requiring performance metrics in license applications helps optimise spectrum usage and mitigate interference, the process must be practical and accessible for private network users. The solutions outlined in this section aim to bridge the knowledge gap by making it easier for users to define their needs without requiring deep expertise in 5G technology.

3.5 Visualisation techniques

We utilised different visualisation techniques for different phases of the tests.

Phase 1 and 2: RF characterisation for the Private Network

Visual representation of RF signal strength across different geographic areas. The signal strength can be mapped using colour gradients, with specific ranges (Good, Fair, Poor) represented by distinct colours.

Figure 10: Physical Location mapping based on RF coverage Areas

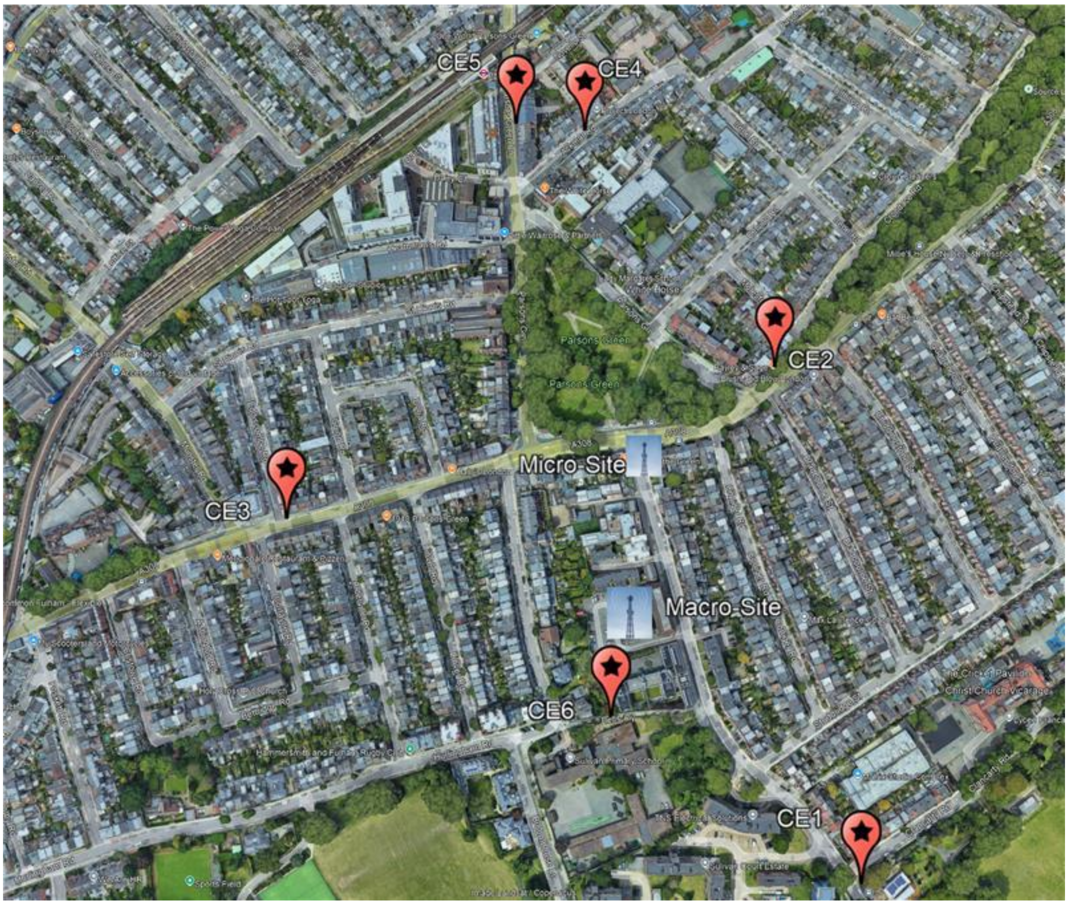

Figure 11: Cell Edge (CE) Locations

<u>Phase 3: Benchmarking Performance Measurements in Identified Locations</u>

Bar charts to compare performance metrics across different RF zones (Excellent, Good, Fair, Poor). Box plots can show the distribution of these metrics to highlight variability and extremes. An example for identified positions locations can be visualised in the map as shown in **Figure 10** and **Figure 11**.

<u>Phase 4: Interference tests performance measurements in identified locations</u>

Bar charts to compare performance metrics across different RF zones (Excellent, Good, Fair, Poor). Box plots can show the distribution of these metrics to highlight variability and extremes. An example for identified positions, locations can be visualised in the map as shown in **Figure 10** and **Figure 11**.

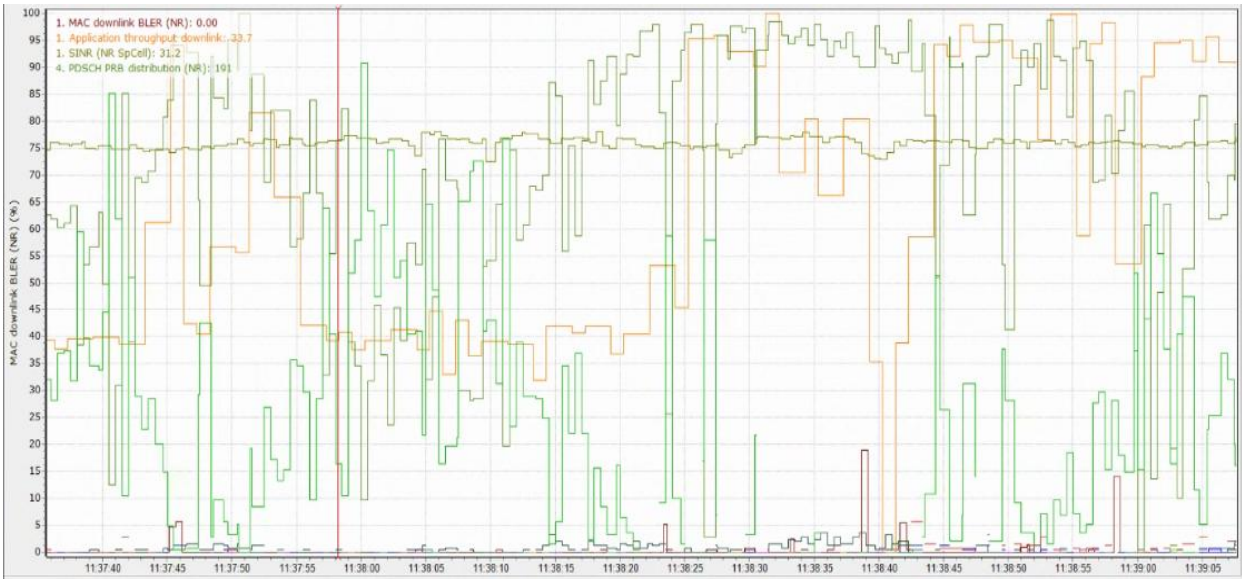

Figure 12: Measurement KPI's distribution

Measured KPI's will help in showcasing high interference impacting areas, allowing regulators to determine the hotspots and avoid assigning intense spectrum sharing for applications that are impacted in the high interference zones. Example visualisation of measured KPI values and cross correlation among different KPI's is shown in **Figure 12**.

The calculated IIM thresholds will show the criteria for high impact hot spots and mapping of IIM metric with physical locations as shown in **Figure 13**.

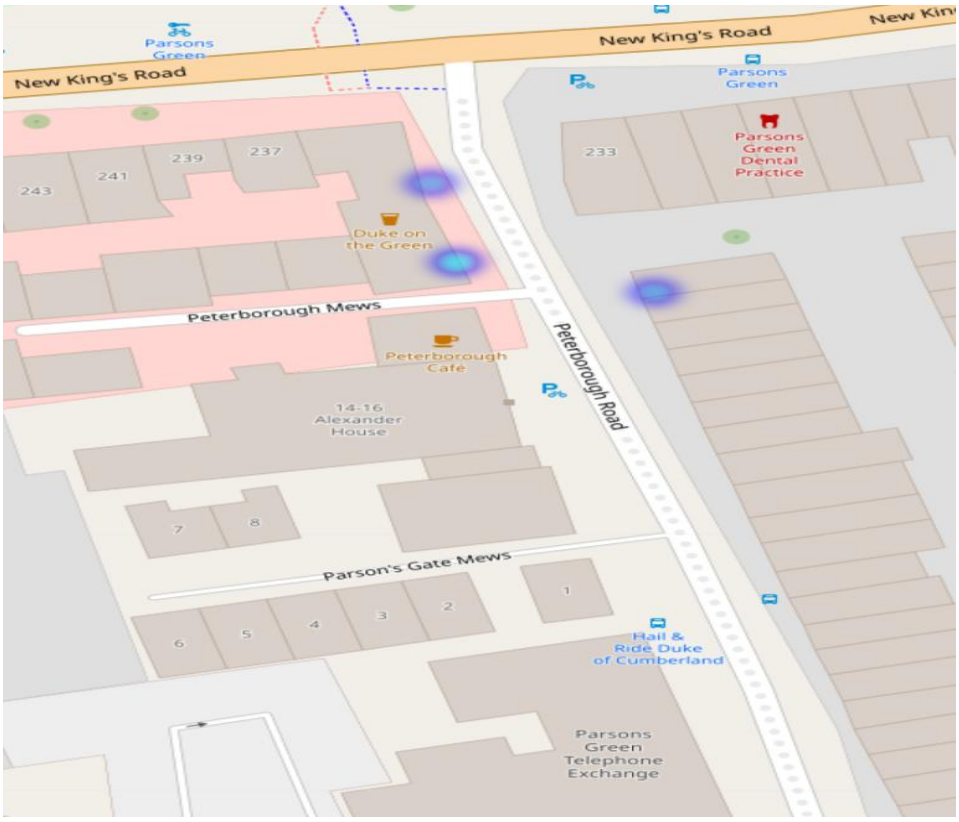

Figure 13: Geographical mapping for IIM

3.6 Details of the PoC demonstration

The demo for the proof of concept of a data sharing solution is aligned with the experiments Digital Catapult carried out to prove the hypothesis that incremental interference due to intense spectrum sharing could be acceptable when the interference does not result in an unacceptable service level degradation.

Digital Catapult conducted several experiments to characterise the RF environment presented in **Table 4** and systematically recorded the measurements of several highly relevant RF parameters during data transfers of mobile devices both in the uplink and downlink directions.

The detailed parameters are presented in **Table 5** for downlink and uplink data transfers, respectively. Detailed analysis for the produced datasets is conducted to generate useful insights on the impact of interference on user experience and the tolerance level(s) for various applications under diverse radio conditions.

For the demo, we utilise two different 5G applications, video streaming and file download, and showcase the performance measurements metrics identified in **Table 5** for both benchmarking and interference tests. This helps us to showcase the impacts of interference on the performance metrics when an adjacent network is present and showcase the tolerance of operations on 5G applications highlighting the possibility of increased spectrum sharing.

The measurements for the PoC demonstration is done as a two-step process defined below:

1. **Step 1**. Benchmarking is executed to characterise the RF environment in the absence of interference from the adjacent cell. The radio conditions thresholds used for characterisation are defined as Excellent (≥75dBm), Good (-75 to -90 dBm), Fair (-90 to -105 dBm) and poor (< -105 dBm) as shown in **Table 4**. Physical location marking the Cell Edge (CE) for the Micro site is also identified and marked as shown in **Figure 11**. In this step the RF areas are identified based on the RF conditions and performance measurements for both 5G applications video streaming and file download are captured on these identified locations.

Step 2: An interference test is executed with the adjacent private network enabled and both 5G applications (video streaming and file download) will be tested at the same physical locations identified in step 1. The results from this measurement will help us to obtain insights into the impact of interference on the 5G applications and help to decide if more aggressive licence sharing can be allowed in the geographical location or not. The details of the measurement KPI's are listed in

2. **Table 5**.
3. **Step 3**: The captured raw data from the Nemo outdoor equipment will be processed and analysed for both the baseline and interference tests. We shall use these data sets to translate the measurements to interference metrics using the IIM framework to showcase the impact for the interference on the user performance in different RF zones.

Table 4: Radio conditions definitions

Radio conditions	Synchronisation Signal Reference Signal Received Power (SS-RSRP) (dBm)	DL Synchronisation Signal to Interference & Noise Ratio (SS-SINR) (dB)
Excellent (cell centre)	≥-75	>25
Good	-75 to -90 (typical value = -85)	15 to 20 (typical value = 17)
Fair	-90 to -105 (typical value = -95)	5 to 10 (typical value = 7)
Poor (cell edge)	< -105 (typical value = -110)	< 5 (typical value = 3)

Table 5: Parameters measured during the field trials

Direction	Measured parameters
Downlink	Received L1 DL throughput [Mbps], Received Application DL throughput [Mbps], UE RSRP [dBm], UE Reference Signal Received Quality (RSRQ) [dBm], UE Physical Downlink Shared Channel (PDSCH) SINR [dB], Multiple Input Multiple Output (MIMO) rank, PDSCH MCS, Medium Access Control (MAC) DL BLER [%],

	PDSCH PRB Utilisation.
Uplink	Received Layer 1 (L1) UL throughput [Mbps], Received Application UL throughput [Mbps], UE RSRP [dBm], PUSCH MCS and PUSCH PRB Utilisation

In deliverable D1.3, we presented the methodology for developing a proof of concept (PoC) data-sharing solution and identified the key requirements and considerations for developing such a solution.

This report presents our vision for a data-sharing solution and established proof points for the feasibility of the solution using common standardised file transfer APIs with appropriate security and authentication mechanisms. We used data collected during the sandbox field trials to develop the proposed PoC data sharing solution.

4. Summary

This report, deliverable D1.7 proof of concept data sharing solution, is part of a series of WP1 deliverables. This report contributes towards the knowledge of feasibility regarding the potential for sharing of usage and interference data for regulatory purposes to improve the efficient use of spectrum. It sets out the potential benefits, associated challenges, and recommendations for the future operation of such systems. In this report, we provided information on two PoC data sharing solutions:

1. **Technology pair 1 - Wi-Fi and mobile in the upper 6 GHz band**: In this case we identified two options:
    a. A possibility to adopt a self-regulating approach where sharing of data with the regulator is not required.
    b. A more flexible sharing arrangement with the cross-technology signalling message shared and reported to an associated destination server using IEEE 802.11bc framework.

    In the report, we demonstrated how the IEEE 802.11bc framework can be utilised to share cross-technology signalling data for regulatory purposes.

2. **Technology pair 2 - Independently operated private networks in the upper n77 band:** In this case we explained the methodology for developing a PoC data-sharing solution. We have also identified the key requirements and considerations for developing a solution. From the data collected during the sandbox field trial, we developed a vision for a solution, and through appropriate PoC and prototyping activities established proof points for the feasibility of the solution using common standardised file transfer APIs with appropriate security and authentication mechanisms.

Appendix A Acronyms

Abbreviation	Definition
AI/ML	Artificial Intelligence/Machine Learning
AP	Access Point
API	Application Programming Interfaces
AR	Augmented Reality
BLER	Block Error Rate
BS	Base Station
CEPT	Cell Edge
CEPT	European Conference of Postal and Telecommunications Administrations
CSV	Comma Separated Values
DSA	Dynamic spectrum access
EBCS	Enhanced Broadcast Services
eMBB	Enhanced Mobile Broadband
ETSI	European Telecommunications Standards Institute
FAQ	Frequently Asked Questions
gNB	Next Generation Node B
GPS	Global Positioning System
HD	High Definition
HLP	Higher Layer Processing
IIM	Interference Impact Metric
IoT	Internet of Things
I/Q	In-phase/Quadrature
IMT	International Mobile Telecommunications
KPI	Key Performance Indicators
MAC	Medium Access Control
mMTC	Massive Machine Type Communications
MCS	Modulation and Coding Scheme
MCX	Mission Critical Communications

Abbreviation	Definition
MIMO	Multiple Input Multiple Output
n77	3800 to 4200 MHz frequency band
OSDaaS	Open Spectrum data as a Service
NR	New Radio
OSI	Open Systems Interconnection
PDSCH	Physical Downlink Shared Channel
PoC	Proof of Concept
PT1	Project Team 1
PRB	Physical Resource Block
PT1	Project Team 1
PUSCH	Physical Uplink Shared Channel
RF	Radio Frequency
RSRP	Reference Signal Receive Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indication
SAL	Shared Access Licence
SCP	Secure Copy Protocol
SDO	Standards Development Organisations
SINR	Signal to Interference and Noise Ratio
UE	User Equipment
UL	Up link
UAV	Unmanned Aerial Vehicle
URLLC	Ultra Reliable Low Latency Communication
VoNR	VoNR - Voice over NR
V2X	Vehicle-to-Everything
VR	Virtual Reality
XR	Extended Reality

References

1 IEEE Standard for Information Technology, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification Amendment 7: Enhanced Broadcast Services, available at: https://grouper.ieee.org/groups/802/11/private/Draft_Standards/11bc/index.html

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

3 5G-Xcast, a 5GPPP Phase II project focused on Broadcast and Multicast Communication Enablers For the Fifth Generation of Wireless Systems, https://5g-ppp.eu/5g-xcast/

4 Electrosense: Open and Big Spectrum Data by Sreeraj Rajendran, Roberto Calvo-Palomino, Markus Fuchs, Bertold Van den Bergh, Héctor Cordobés, Domenico Giustiniano, Sofie Pollin and Vincent Lenders, IEEE Communications Magazine, Volume 56, Number 1, January 2018, https://dspace.networks.imdea.org/bitstream/handle/20.500.12761/498/08121869.pdf?sequence=1

5 https://en.wikipedia.org/wiki/Lambda_architecture

realwireless
independent telecoms experts

Real Wireless Ltd
PO Box 2218
Pulborough
West Sussex
RH20 4XB
United Kingdom

t +44 207 117 8514
f +44 808 280 0142
e info@real-wireless.com
w real-wireless.com
real-wireless

Copyright ©2025 Real Wireless Limited. All rights reserved. Registered in England & Wales No. 6016945