Spectrum Sandbox Deliverable 2.4: WP2 Simulate performance of solutions (Fixed links/UWB/Receiver only/ and Mobile)

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Abbreviations

5G NR	5th generation New Radio
ACLR	Adjacent channel leakage ratio
dB	Decibels relative to other powers
dBm	Decibels relative to a milliwatt
EIRP	Effective Isotropic Radiated Power
MIMO	Multiple-Input Multiple-Output
NLoS	Non-Line-of-Sight
NR-ARFCN	New Radio - Absolute Radio Frequency Channel Number
OOB	Out-of-band
PCI	Physical Cell ID
PSD	Power Spectral Density
QoE	Quality of Experience
RAS	Radio Astronomy Service
RSSI	Received Signal Strength Indicator
SS RSRP	Synchronization Signal - Reference Signal Received Power
UE	User Equipment
UWB	Ultra-Wide Band
WP	Work Package

1. Introduction

1.1 Project background

Spectrum sharing is a way to optimize the use of the airwaves, or wireless communications channels, by enabling multiple categories of users to safely share the same frequency bands. It has become necessary due to growing demand crowding the airwaves. Smartphones, the Internet of Things, military and public safety radios, wearable devices, smart vehicles and countless other devices all depend on the same wireless bands of the electromagnetic spectrum to share data, voice and images.

Ofcom also set out its plans for spectrum sandboxes in its Spectrum Roadmap, to inform the development of new solutions for enhanced sharing. The primary objective of the sandboxes would be to provide data to support the possibilities and role of more intensive spectrum sharing by an appropriate authorisation model.

Specifically, we see that the sandbox projects work packages can provide the following:

- Work packages 1 (WP1) – Spectrum sandbox testbeds
- Work packages 2 (WP2) – Simulation and modelling
- Work packages 3 (WP3) – Economic and regulatory assessment

And the system 'pairs' of spectra could include

- Wi-Fi and mobile
- Independently operated private networks
- Mobile and fixed links
- UWB and mobile
- Receive-only users (scientific applications) and mobile

1.2 Project scope

The project aims to investigate the possibilities and implications of increased spectrum sharing between different spectrum users and services. This would be achieved by selecting a relevant set of spectra sharing user/service pairs and using sandboxes to assess the practical feasibility and scalability, net (potential) benefits as well as economic and regulatory considerations of each of these spectrum sharing solutions. The project should ultimately provide valuable information to the government and regulator on whether and how to deploy a more intensive spectrum sharing system.

The sandboxes involve practical field trials to test the feasibility of the selected spectrum sharing pairs within the scenario and parameters of the testing environment (e.g. no harmful interference), followed by simulations to broaden the scope of parameters and scenarios being tested per spectrum pair (e.g. scalability).

Work package 2 simulation and modelling simulates spectrum sharing solutions for different technical parameters, locations, frequencies, and technologies as well as solutions, and assess the outcomes, which may include benefits such as:

- Reduced network deployment costs to achieve desired coverage and capacity, and how cost savings, or burdens, are distributed between systems
- Improved (or degraded) network performance and QoE
- Increased efficiency in the use of spectrum

WP2 simulation platform would calibrate and simulate the different use cases and scenarios with the different spectrum sharing solutions, as shown in Figure 1.

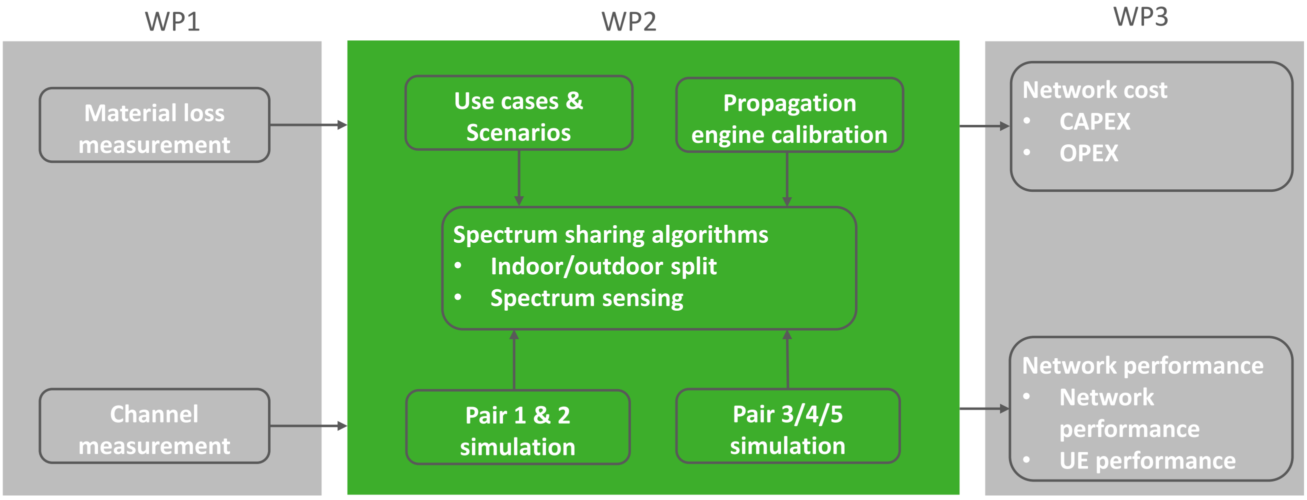


Figure 1: Simulation structure of WP2, input from WP1 and output to WP3

First, the simulation platform calibrates the radio channel and materials by the measured received signal strength and material loss data from WP1 Channel measurements in the upper 6 GHz band for the first two pairs: mobile and Wi-Fi and independently operated private networks.

Second, the simulation platform simulates the cost, coverage, capacity and QoE for all five pairs, and outputs the results to WP3 for an economic analysis of benefits and costs associated with each spectrum sharing solution.

This deliverable simulates the different use cases and scenarios for Fixed link and mobile, UWB and mobile, and Receiver-only and mobile pairs, and compares the performance of spectrum sharing for these pairs. The deliverable is organized as follows: Section 2 introduces the spectrum sharing mechanisms and the related key parameters in the simulation, Section 3 evaluates the simulation results of different scenarios, and finally Section 4 provides the conclusions and details possible future work.

2. Spectrum sharing mechanisms

An effective spectrum sharing framework between system pairs has the potential to maximise consumer benefits. In the sandbox, two sharing mechanisms have been developed to simulate the spectrum sharing performance and benefits.

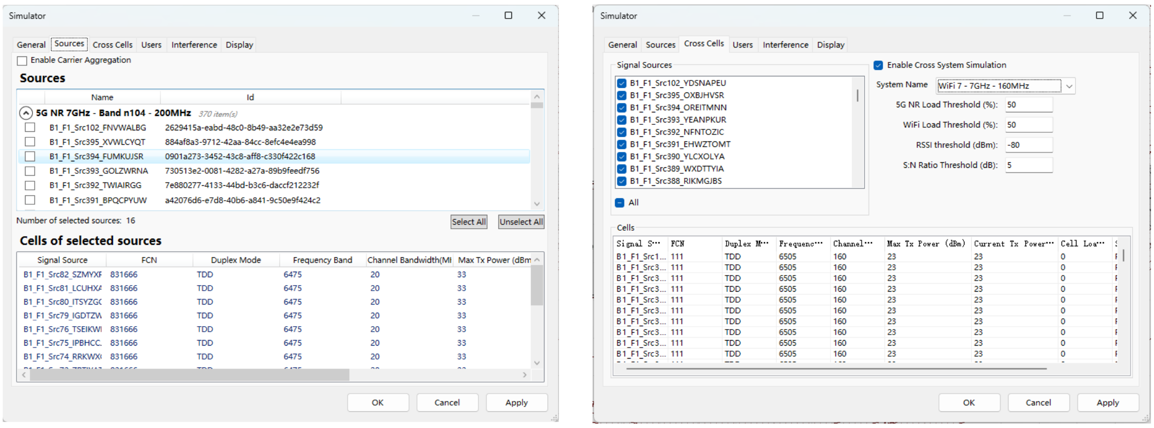
2.1 Geographic separation

Geographic separation can effectively mitigate the interference between two services by radio propagation effect. By defining exclusion radii (e.g., 50–100 km) around one service site, the other service can coexist with protected sub-bands of the service and implement spectrum sharing.

2.2 Spectrum sensing mechanism

Spectrum sensing technique is another spectrum sharing mechanism for the system pairs, where the spectrum would be split into different channels, and both systems would be able to use all bands or all channels if the other service is not present.

"Sense and avoid" techniques for each system would be implemented in the simulation platform, as illustrated in Figure 2, where 5G NR and Wi-Fi systems would share the upper 6 GHz spectrum. In the simulation, 5G NR and Wi-Fi systems are configured separately, and a RSSI threshold would be set to avoid the co-channel interference when enabling the mobile and Wi-Fi spectrum sharing cross-system simulation, i.e. when the signal levels of two adjacent mobile cell and Wi-Fi AP with co-channel is larger than the set threshold, the mobile cell would move away from the channels to some channels that are not deployed.



(a) 5G NR system configuration

(b) Wi-Fi system configuration

Figure 2: Spectrum sensing configuration in the simulation

3 Simulation performance of solutions

This section presents the performance of the simulation results of the sharing mechanisms, and outputs the simulation data into WP3 for the economic analysis.

3.1 Use case

WP2 simulates the other three system pairs and evaluates the network performance and spectral efficiency improvement by the use of spectrum, as shown in Table 1.

Table 1: use cases introduction

Pairs	Technical modelling	Shared spectrum	Use cases	Sharing mechanisms
Fixed link and Mobile	WP2	Upper 6 GHz	Safety critical applications such as remote operation of vehicles/machinery	Spectrum sensing

UWB and Mobile	WP2	Upper 6 GHz	Spread spectrum UWB radar for through-wall imaging, e.g. in law enforcement situations	Spectrum sensing
Receiver-only (Scientific stations) and Mobile	WP2	Upper 6 GHz	Use of mobile network in the vicinity of radio-astronomy receivers	Geographic separation

3.2 Fixed links and mobile

Fixed link radio networks serve as critical backhaul infrastructure for mobile networks, providing stable, high-capacity connections between two or more fixed points. These links operate within dedicated frequency bands and are designed to support spectrum sharing with minimal interference. Techniques such as spatial orthogonality, adaptive beamforming, and interference coordination are essential in enabling coexistence with mobile networks while maintaining reliable transmission.

3.2.1 Scenarios and network

The simulation was conducted in Central London, representing an urban environment with an area of approximately 64 km^2, including terrain variations, as shown in Figure 3, where fixed link base stations and mobile base stations are deployed, and the location of fixed link stations is shown in Table 2.

(a) Fixed link case

(b) 3D view

Figure 3: Fixed link case

Table 2 Base station parameters

Latitude(Deg)	Longitude(Deg)	Height(m)	Tx power (dBm)	Antenna Azimuth	Antenna Tilt
51.493533	-0.166526	25	30	32.67098061	1.637162933
51.500082	-0.15961344	63	30	212.6762601	-1.644942807

The fixed link uses a narrow beam antenna as shown in Figure 4, where the narrow beam width is 6 degrees, and the antenna gain is 29.12 dBi.

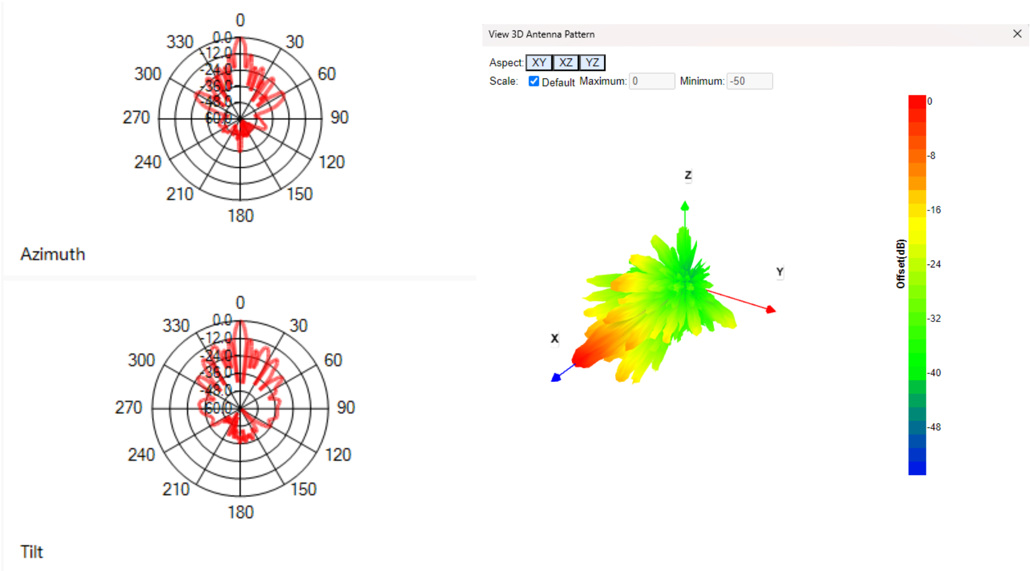


Figure 4: Antenna pattern for fixed link

3.2.2 Network performance

Network sharing performance, including network efficiency, UE performance, and cost-effectiveness, is evaluated for both mobile and fixed links. The analysis incorporates interference threshold calculations to assess signal quality, link reliability, and co-channel interference. Additionally, a path loss simulation is conducted to visualize network coverage and signal attenuation in an urban setting. To evaluate interference-limited performance, the single-entry interference threshold I is computed as:

$$I = \sum I - 10\log_{10} n,$$

Where $\sum I$ represents the total interference power budget, and n is the number of equal single-entry interferers, typically set to four. The aggregate interference threshold is given by $\sum I = N - 5.9$ dB for most frequency bands. The noise power N includes system noise figure and receiver sensitivity. Based on this, the wanted-to-unwanted (W/U) ratio, which defines the interference protection limit, is determined as:

$$\frac{W}{U} = R_W - I,$$

where R_W is the reference power level. This approach ensures that the received signal power remains above the interference level, preserving adequate SINR and system throughput. To complement the interference calculations, a path loss simulation has been conducted for selected locations in the western part of Central London. The simulation follows standardized propagation models, incorporating urban obstructions and diffraction effects to model real-world signal attenuation.

3.2.2.1 Simulation environment and results

The parameters of Fixed links are defined in **Error! Not a valid bookmark self-reference.**, where the received power is -126dBW/40MHz, i.e. -128dBm @SS RSRP, which means the mobile signal to fixed link station should be less than -128dBm.

Table 3: System Configuration, Interference Analysis, and Antenna Parameters [1]

Parameter	Value
Frequency Range	6.425 - 7.125 GHz
Bandwidth	40 MHz
Receiver Sensitivity	-98 dBW

Wanted-to-Unwanted (W/U) Ratio	28 dB
Maximum Interference Received Power	-126 dBW/40MHz
Interference Threshold	-128 dBm @ SS RSRP
Antenna Gain	29.12 dB
Beamwidth (Narrow Beam)	6 degrees
Front-to-Back Ratio	35.6 dB
Spectrum Sensing Mechanism	Based on Interference Threshold

Based on the downlink and uplink reciprocity of path loss, we can simulate the path loss according to the interference threshold, as shown in Figure 5, i.e. DL path loss = UL path loss, if the same band is used. We can calculate the path loss, i.e.

- define the interference threshold, i.e. maximum received signal from mobile to fixed links station, i.e. EIRP_mobile – uplink path loss <= interference threshold,
- calculate the uplink path loss, i.e. uplink path loss = EIRP_mobile - interference threshold.
- utilize the reciprocity, downlink path loss = EIRP_mobile – interference threshold

Based on the calculation, we can simulate fixed links station and generate the heat map of path loss, and determine the protection area. Once mobile is deployed outside the protection area, signal from mobile to fixed links station will be less than interference threshold.

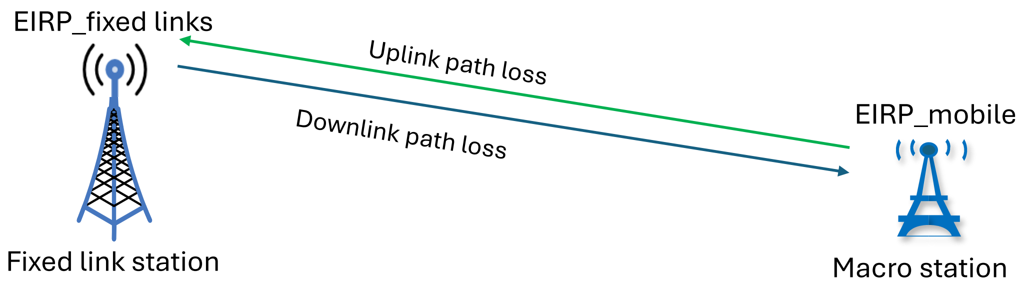


Figure 5: downlink and uplink reciprocity of path loss

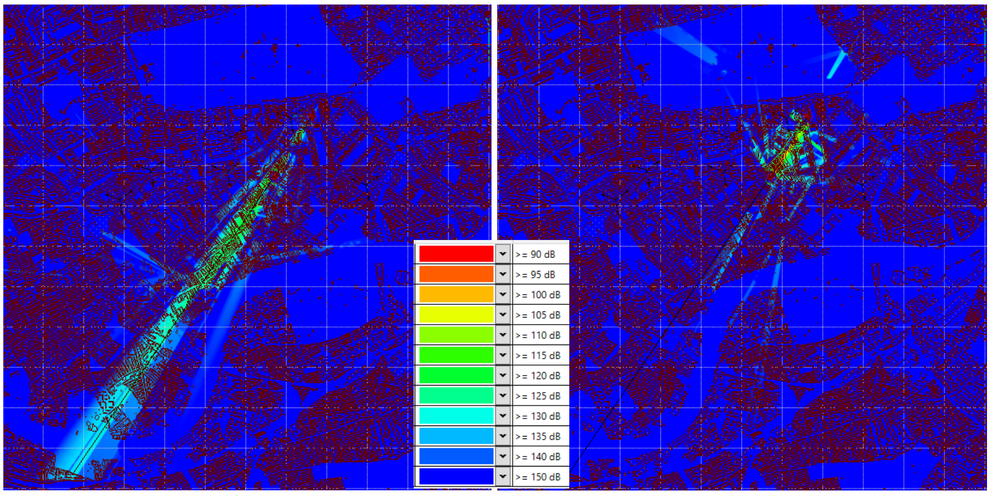
Assuming the mobile base station EIRP is 64.88dBm/100MHz, the path loss threshold is 151.7dB. Based on the threshold, we can simulate the protection area so as that the interference is less than the interference threshold of fixed links when the mobiles are deployed outside the protection area.

3.2.2.2 Analysis of fixed links path loss simulations

Figure 6 provides a comprehensive analysis of the fixed link path loss simulations for different scenarios. The results illustrate the signal attenuation characteristics and the impact of urban structures on link reliability. The simulation incorporates path loss modelling and interference threshold calculations to assess the performance of multiple fixed links in an urban environment.

In Figure 6a, the axes delineate the extent of signal propagation, revealing how Fixed Link 1 performs under typical urban conditions. The heatmap indicates that Fixed Link 1 achieves relatively stable coverage over long distances. However, due to obstructions caused by high-rise buildings along the transmission path, signal attenuation occurs rapidly, leading to coverage gaps. Despite these challenges, the link demonstrates strong propagation capabilities, maintaining adequate received signal power in open areas. The interference effects along the link path are minimal, indicating a well-managed frequency allocation strategy.

In Figure 6b, the impact of environmental variations on Fixed Link 2 are evident. The coverage area appears more limited compared to Fixed Link 1, with notable signal degradation near dense urban structures. The presence of multiple obstacles introduces additional diffraction and reflection effects, which contribute to increased co-channel and adjacent-channel interference. The link exhibits relatively lower robustness to environmental changes, with localized high path loss regions forming around obstructed areas. These results highlight the importance of site-specific link deployment to mitigate interference and signal attenuation.



(a) Fixed link 1 only (b) Fixed link 2 only

Figure 6: Fixed link path loss simulations

3.2.2.3 Spectrum sharing performance

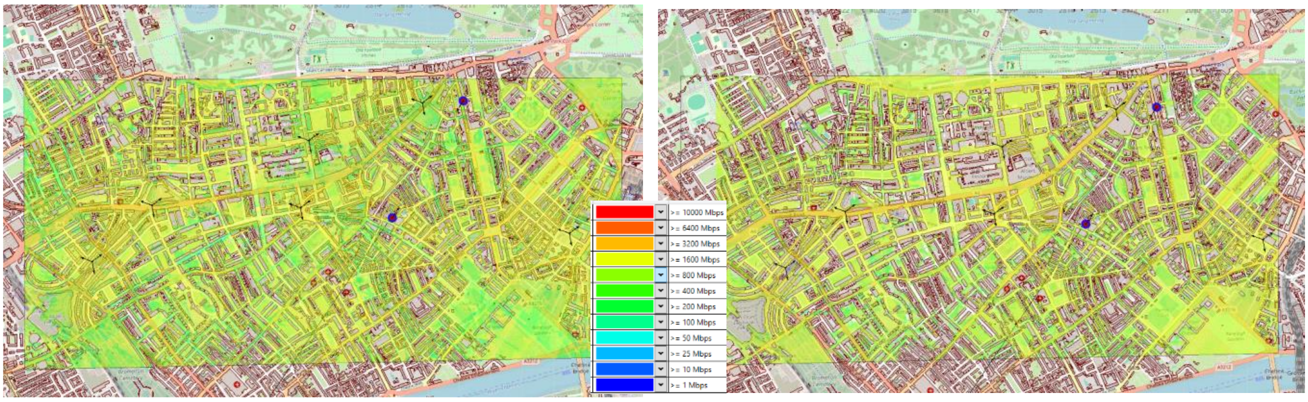
Spectrum sensing mechanism is used to simulate the capacity performance, where the interference threshold is set according to Table 3, and mobile base stations are deployed outside the protected area, as shown in Figure 3(a) and Figure 6. The simulation parameters are listed in Table 4.

Table 4: simulation parameters

Parameters	Configuration	
Wireless System	5G NR	5G NR
Carrier Frequency	n78 3.5 GHz	Upper 6 GHz
Channel Bandwidth	100 MHz	100MHz
Cell Tx Power per Port	43 dBm	46 dBm
Antenna Gain	15.88 dBi	15.88 dBi
Duplex	TDD (DL: 80%)	TDD(DL: 80%)

MIMO	4x4	4x4
Cell EIRP	64.88 dBm	67.88 dBm

With spectrum sharing, -128dBm sensing threshold is set for selecting the different channels, where upper 6 GHz channels with 100 MHz bandwidth are used for spectrum sharing to reduce the interference. Figure 7 and Table 5 show the throughput of the 3.5 GHz band and the upper 6 GHz band. From the table, the average throughput per cell is 826.9 Mbps for 3.5 GHz band; while additional upper 6 GHz band is used with spectrum sharing, the additional capacity is provided, about average 733Mbps per cell, which means that re-using the upper 6 GHz band with spectrum sensing solution improves network performance and increases efficiency in the use of spectrum.



(a) throughput of 3.5 GHz (b) throughput of upper 6 GHz

Figure 7: Throughput of 3.5 GHz and upper 6 GHz bands

Table 5: throughput performance with additional sharing band

	3.5 GHz band	upper 6 GHz band with sharing
Average throughput (Mbps)	826.9	733.0

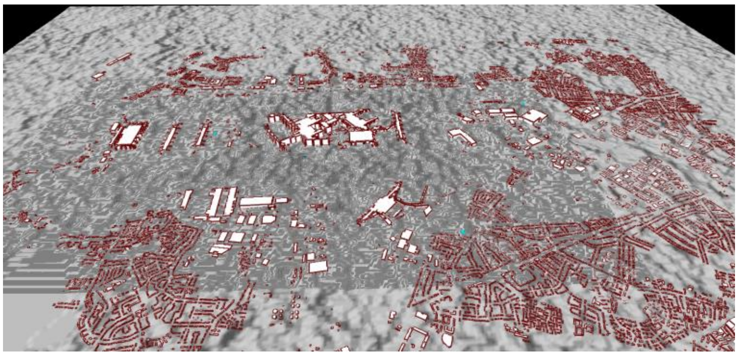
3.3 UWB and mobile

UWB is a radio technology that is low power and has a relatively high data transfer rate. It operates in wide bandwidths of 500 MHz (or more), currently within the range of 3.1 to 10.6 GHz, which overlaps with upper 6 GHz band. However, due to its orthogonal code characteristics, UWB user power remains below the noise floor, resulting in limited interference with mobile networks. This enables the possibility of simulating and evaluating spectrum sharing between UWB and mobile networks.

3.3.1 Scenarios and network

The simulation was conducted at London Heathrow Airport, an environment with high-density wireless activity and large-scale infrastructure that influences UWB propagation characteristics, as shown in Figure 8, where the location of UWB stations is listed in Table 6.

(a) UWB case



(b) 3D view

Figure 8: UWB and mobile case

Table 6: UWB station parameters

Latitude (Deg)	Longitude (Deg)	Height (m)	Tx power (dBm)	Antenna Azimuth	Antenna Tilt
51.47515011	-0.41909516	10	-2.85	180	-5
51.45615686	-0.43771493	10	-2.85	180	-5
51.47146761	-0.47401646	10	-2.85	180	-5

3.3.2 Network performance

Network sharing performance, including network efficiency, UE performance, and cost-effectiveness, is evaluated for both mobile and UWB (Ultra-Wideband) pairs, following the same methodology used for mobile and fixed link pairs. However, due to the unique signal characteristics of UWB, particularly its wide bandwidth and low power spectral density, interference threshold calculations and propagation modelling require a different approach.

Unlike conventional narrowband systems, UWB operates over a broad frequency range with low transmission power, making it resilient to certain types of interference but more susceptible to environmental obstructions and co-channel coexistence challenges. The total interference threshold for UWB in the upper 6 GHz frequency band is calculated using the power spectral density and total bandwidth as:

$$I = P_d - SNR_{min} - Margin,$$

where I represents the interference threshold, P_d is the received signal power, SNR_{min} is the minimum required signal-to-noise ratio for reliable communication, and the $Margin$ accounts for additional losses due to fading, interference, and hardware constraints. The PSD for UWB operation within the upper 6 GHz band stands at -41.3 dBm/MHz and the extent of total bandwidth establishes how interference contributes effectively. When signal attenuation or blockage reduces P_d, the interference threshold drops thus increasing UWB link susceptibility to degradation.

Table 7: UWB System Configuration, Interference Analysis, and Antenna Parameters [2][3][4][5]

Parameter	Value
Frequency Band	7000 MHz
Bandwidth	500 MHz
Transmit Power	-41.3 dBm/MHz

Antenna Gain	6 dBi
Received Signal Power (P_d)	-95 dBm
Minimum Required SINR (SNR_{min})	16.6 dB
Additional Loss Margin (Airport Environment)	5 dB
Interference Threshold	-116.6 dBm/Hz
Sharing Mechanism	Spectrum Sensing
UWB Interference Impact	Significant interference to mobile
Beamwidth (Horizontal/Vertical)	360° (H) / 90° (V)

3.3.2.1 Simulation environment and results

The parameters are defined in Table 7.

- UWB transmitters were deployed in a flat 8000 × 8000 km^2 airport environment with varied obstruction levels.
- Interference analysis focused on UWB coexistence with 5G NR and radar systems.
- Interference threshold was calculated based on signal power and SINR requirements.
- Spectrum sensing was used to manage co-channel interference, allowing UWB to coexist with mobile systems.

The results showed that UWB operates efficiently in high-interference environments, but significant signal degradation was observed in high-obstruction zones. In particular:

- High-power radar and mobile base stations caused increased interference, leading to localized coverage gaps.
- Interference threshold for reliable UWB operation ranged from -110 dBm to -120 dBm, depending on system load.

3.3.2.2 Analysis of UWB path loss simulation

Following the same methodology used for mobile and fixed link pairs, i.e. downlink and uplink reciprocity of path loss, we simulate the path loss of UWB stations to determine the protection area of UWB according to the interference threshold. Assuming the mobile base station EIRP is 58.7dBm/100MHz, so the path loss threshold is 93.3 dB if the received signal threshold is -116.6dBm/Hz.

Figure 9 illustrates the UWB signal distribution and path loss heatmap at Heathrow Airport. The green regions represent areas of strong signal coverage, while blue areas indicate significant signal attenuation caused by obstructions such as airport buildings, terminals, and parked aircraft. The simulation results show UWB has 150m protection distance due to the unique signal characteristics of UWB, which means the mobiles outside the protection distance will have low signal level to the UWB stations, so the interference will be lower than the interference threshold.

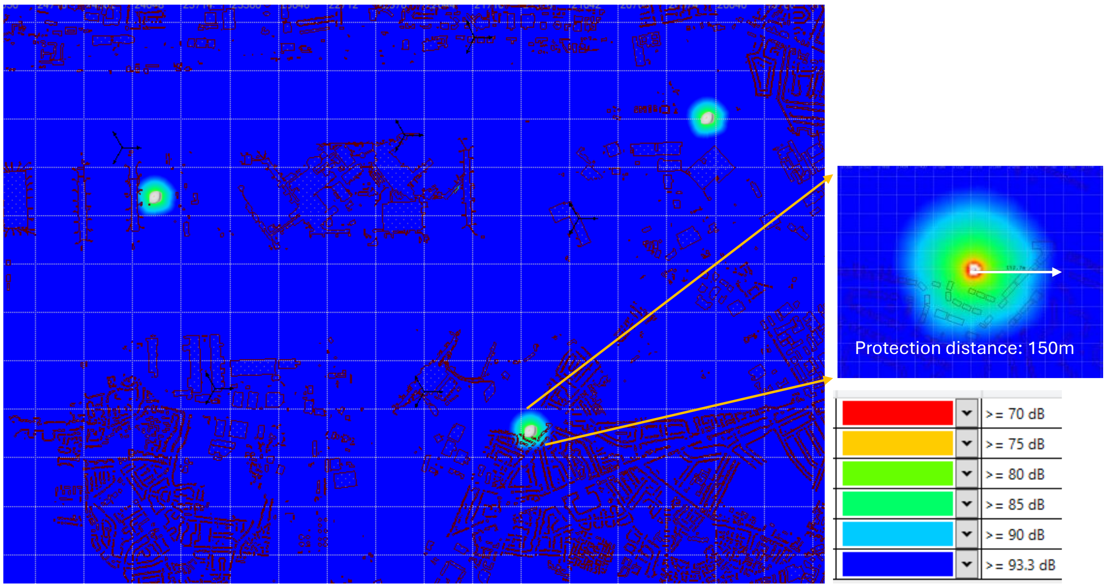
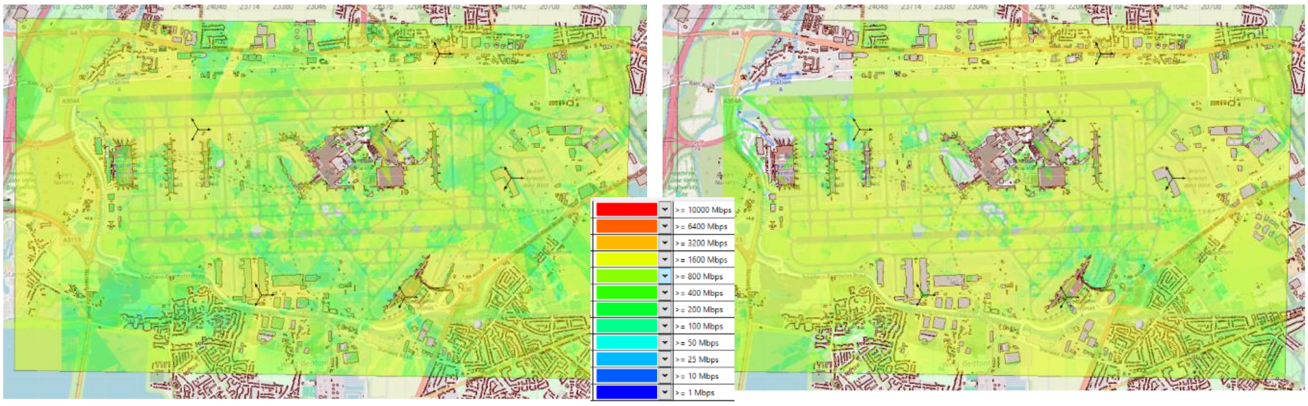


Figure 9: UWB path loss simulations

3.3.2.3 Spectrum sharing performance

Spectrum sensing mechanism is used to simulate the capacity performance, where the interference threshold is set according to Table 7, and mobile base stations are deployed outside the protected area, as shown in Figure 8(a) and Figure 9. The simulation parameters are listed in Table 4.

With spectrum sharing, -116.6 dBm sensing threshold is set for selecting the different channels, where upper 6 GHz channels with 100 MHz bandwidth are used for spectrum sharing to reduce the interference. Figure 10 and Table 8 show the throughput of the 3.5 GHz band and upper 6GHz band. From the table, the average throughput per cell is 992.9 Mbps for 3.5 GHz band; while additional upper 6 GHz band is used with spectrum sharing, the additional capacity is provided, about average 970.5Mbps per cell, which means that re-using the upper 6 GHz band with spectrum sensing solution improves network performance and increases efficiency in the use of spectrum.



(a) throughput of 3.5 GHz

(b) throughput of upper 6 GHz

Figure 10: throughput of 3.5 GHz and upper 6 GHz bands

Table 8: throughput performance with additional sharing band

	3.5 GHz band	upper 6 GHz band with sharing
Average throughput (Mbps)	992.9	970.5

3.4 Receiver-only and mobile

Receiver-only scientific stations or Radio Astronomy Service (RAS) Stations rely on observing faint celestial signals, such as hydrogen line emissions and molecular spectral lines. Thus, they require ultra-quiet spectral environments, with interference thresholds as low as -188.1 dBm/50KHz [6]. In contrast, mobile networks operate with transmit powers up to tens of watts, creating significant out-of-band (OOB) emissions and adjacent channel leakage ratio (ACLR) risks. The wide bandwidths demanded by 5G/6G further exacerbate potential overlaps with Receive-only protected sub-bands.

3.4.1 Scenario and network

The study area is Jodrell Bank Centre, approximately 100 by 60 km^2 rural area, as shown in Figure 11.

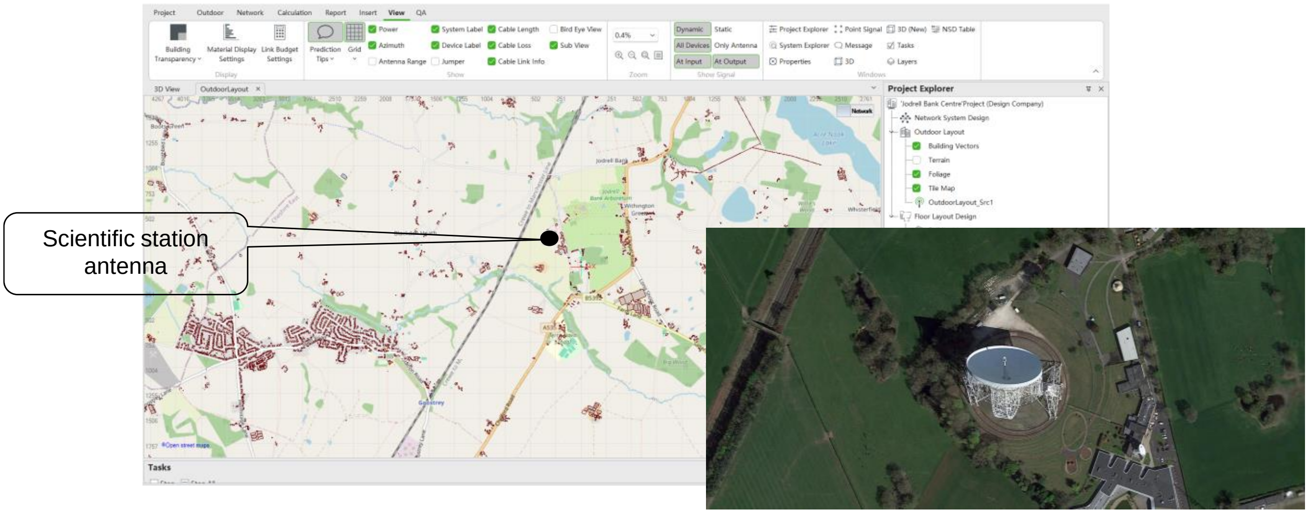


Figure 11: Receiver-only case – Jodrell Bank centre

3.4.2 Spectrum sharing challenges and protection strategies

In passive scientific applications, interference protection is governed by strict regulatory limits, particularly ITU-R RA.769 [6], which defines the permissible interference levels required to avoid signal degradation. As mobile station deployments increase, the received power at passive receivers is affected by unwanted emissions, necessitating protection strategies such as:

- Geographic separation between mobile base stations and sensitive scientific sites to minimize interference.

3.4.2.1 Simulation configuration

The simulation configuration is listed in Table 9.

Table 9: Simulation configuration

Parameters	Configuration
Wireless System	5G NR
Carrier Frequency	6.650 – 6.6752 GHz

Channel Bandwidth	25.2 MHz
Received-only station height	50 m
Mobile base station height	18 m (rural)/20 m (urban)
Cell Tx power per port	43dBm
Interference threshold	-188.1 dBm/50KHz

Based on the same methodology of UWB and mobile, i.e. downlink and uplink reciprocity of path loss, we can simulate path loss according to the interference threshold. Assuming the mobile cell transmits power 43 dBm, leads to the Path loss threshold being 200.1 dB.

3.4.4.2 Analysis of interference impact on Receiver only

Figure 12 illustrates the interference distribution around the Jodrell Bank Centre, a major radio astronomy observatory in the UK. The heatmap represents regions where strong emissions from mobile networks create high-power interference zones, potentially exceeding acceptable thresholds for radio telescopes and other passive scientific applications. The yellow and green regions indicate areas with high signal interference, while blue regions show areas with low interference impact.

The interference pattern in Figure 12 highlights the need for proactive spectrum management, as mobile transmissions can degrade radio telescope observations and scientific measurements.

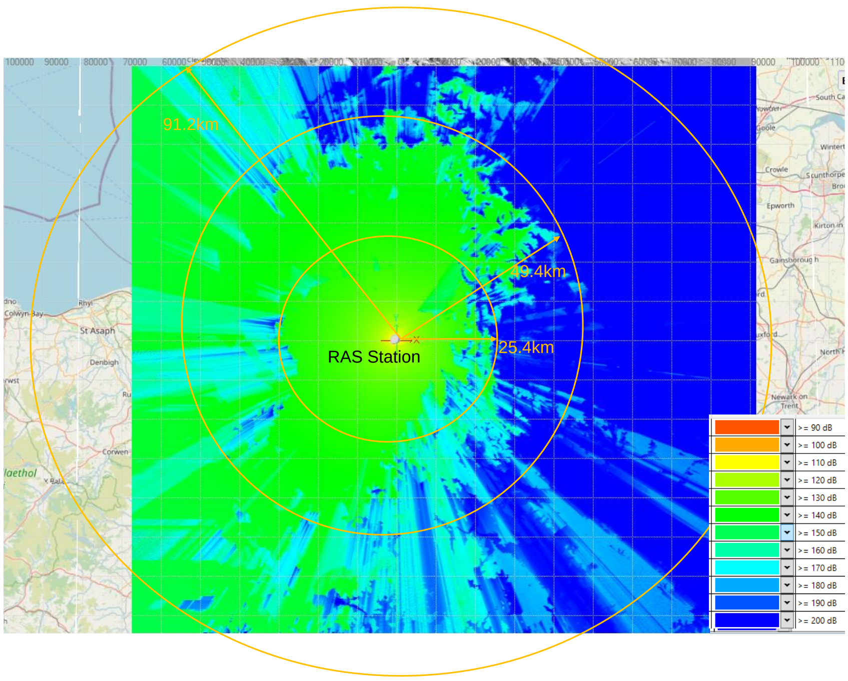


Figure 12: Receive only protected distance

From Figure 12, we can confirm that

- In rural scenarios, the blue area can deploy a mobile base station, with the worst-case protection distance being > 91 km
- Hills can block the signal from the base station to scientific stations, so the spectrum can be reusable, as shown in Figure 13.
- The interference from mobiles, deployed outside the protection area, to receiver-only stations will be less than the interference threshold. So geographic separation sharing mechanism is used to re-use the scientific band.
- This protection distance is case-by-case. For the dense urban with high rise building, the reusable distance is small. So here the simulation tool will be needed to evaluate the use case.

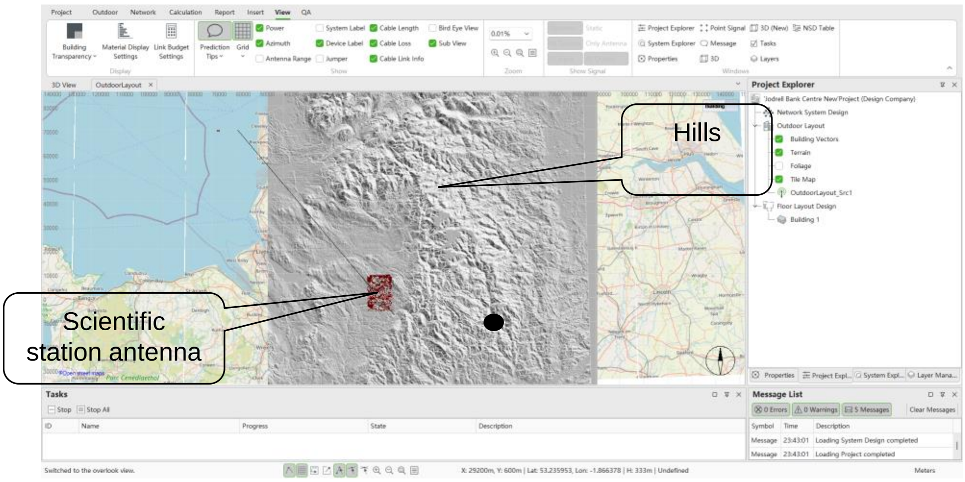


Figure 13: interference block

4. Conclusions

This deliverable simulates the performance of spectrum sharing for Fixed links/UWB/Receiver only and Mobile. The simulation results provide a detailed assessment of path loss performance and analyse the protected area and deployment area based on the interference model and threshold. Simulation results show, the mobile can re-use the upper 6 GHz bands, deployed for fixed links/UWB/Receiver-only, by some simple spectrum sharing mechanisms, and the shared upper 6 GHz band provides the additional capacity to improve the network performance and QoE and increase the efficiency in the use of spectrum.

Future work should explore advanced interference management techniques, such as beamforming and adaptive power control, to further improve coexistence between these pairs. The integration of AI-driven spectrum allocation strategies may also enhance spectral efficiency by dynamically adjusting network configurations in real-time. The insights from this study underscore the importance of integrating mobile base stations within upper 6 GHz radio channel to maximize spectrum efficiency and improve overall connectivity in next-generation wireless networks.

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