Spectrum Sandbox Deliverable 2.3: WP2 Simulate Performance of Solutions: Mobile and Wi-Fi, IOPN

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Abbreviations

5G NR	5th generation New Radio
AP	Access Point
BS	Base Station
CAPEX	Capital Expenditure
CAV	Connected and Autonomous Vehicles
dB	Decibels relative to other powers
dBm	Decibels relative to a milliwatt
EIRP	Effective Isotropic Radiated Power
IOPN	Independently operated private networks
LOS	Line of Sight
LTE	Long Term Evolution
MIMO	Multiple-Input Multiple-Output
NLOS	Non-Line of Sight
OPEX	Operating Expense
PSC	Permanent Subscriber Identity Code
PSU	Power Supply Unit
QoE	Quality of Experience
RSSI	Received Signal Strength Indicator
SS RSRP	Synchronization Signal - Reference Signal Received Power
UE	User Equipment
UWB	Ultra-Wide Band

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.

Spectrum sharing is necessary because growing demand is 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 sandbox projects could provide the following work packages:

- 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 (IOPN)
- Fixed links and mobile
- 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 user and service types. This would be done 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 includes 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 quality of experience (QoE)
- Increased efficiency in the use of spectrum

WP2 simulation platform calibrates the ray-tracing propagation model first and then simulate the different use cases and scenarios with the different spectrum sharing solutions, as shown in Figure 1.

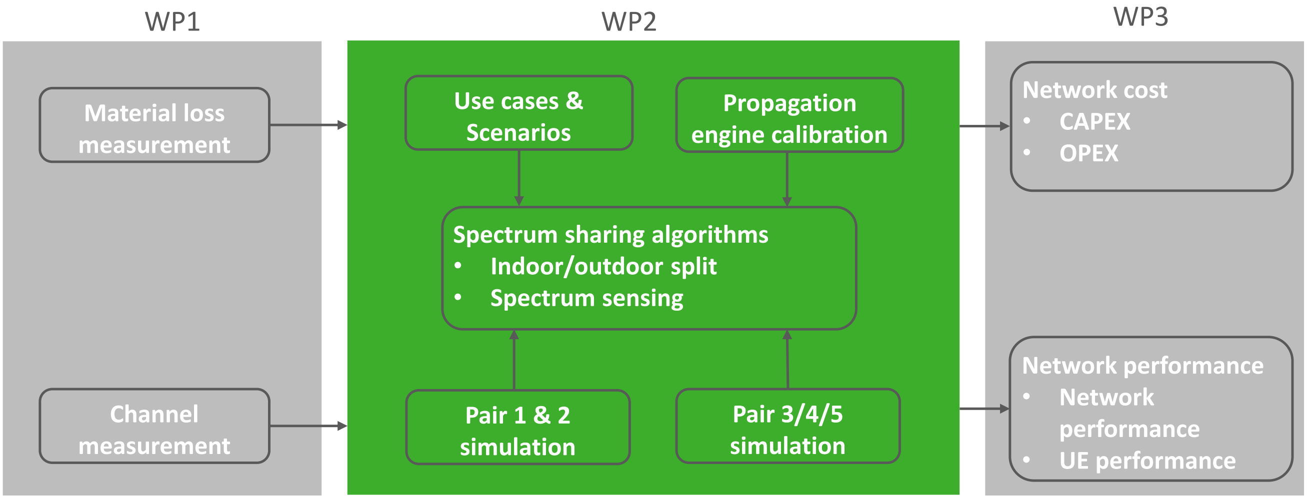


Figure 1: simulation structure of WP2, input from WP1 and output to WP3

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 and n77 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 output the results to WP3 for an economic analysis of benefits and costs associated with each spectrum sharing solution.

This deliverable introduces the calibration and simulation of different use cases and scenarios for mobile and Wi-Fi pair, and independently operated private networks pair, and output the network performance and cost to WP3. The deliverable is organized as following: Section 2 discusses the channel measurement and calibration of ray-tracing propagation engine in simulation platform, Section 3 introduces the spectrum sharing mechanisms and the related key parameters in the simulation, Section 4 evaluates the simulation results of different scenarios for Pair 1&2, and the final Section 5 provides the conclusions and details possible next works.

2 Radio propagation engine verification and calibration

Simulation platform sets the default material loss and environmental parameters for ray-tracing propagation engine to calculate the signal coverage and capacity for different use cases and scenarios, but the different use cases and environments have possibly different materials, material loss, and environment parameters, so there needs to calibrate the propagation engines for providing the accurate simulation data for WP3 economic analysis.

2.1 Material penetration loss measurement

When simulating the outdoor-to-indoor scenarios, the signal from outdoor macro base stations penetrate the building to provide the indoor coverage, therefore, the material loss would impact the performance of simulation.

WP1 measures the material loss for WP2 to configure the transmission loss in material database of simulation platform, as shown the measurement scenarios in Figure 2.

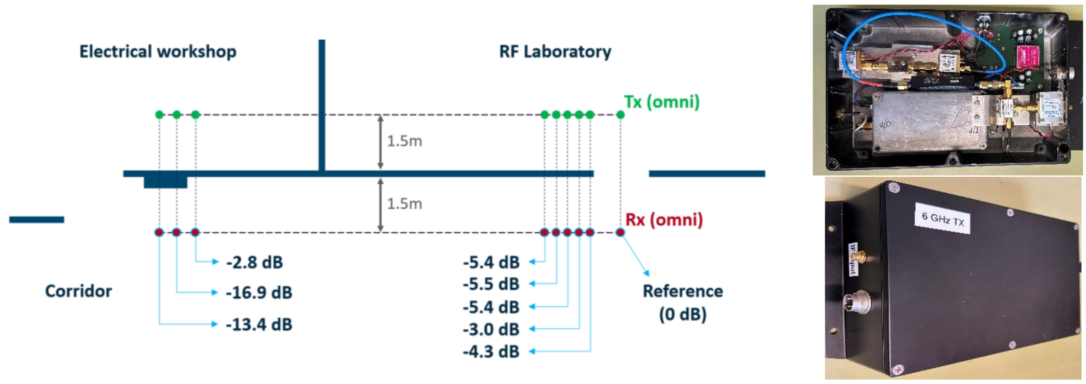


Figure 2: material loss measurement

Table 1 lists the measured results for different materials at 5 GHz and 6.515 GHz bands. These measured results can be imported into simulation platform for simulation calculation, as shown in Figure 3, where all losses, including transmission loss, reflection loss, and diffraction loss, are managed by the Material Database in the WP2 simulation tool.

Table 1: material loss

Material	dB Loss at 5 GHz	dB Loss at 6.515 GHz
Reinforced concrete (203 mm)	55	63
Concrete (203 mm)	48	54
Brick-faced concrete	41	48
Brick-faced masonry block	32	43
Concrete (102 mm)	22	25
Brick	15	15
Masonry block	15	16
Lumber (Dry – 38 mm))	3	4
Glass (6 mm)	1	1

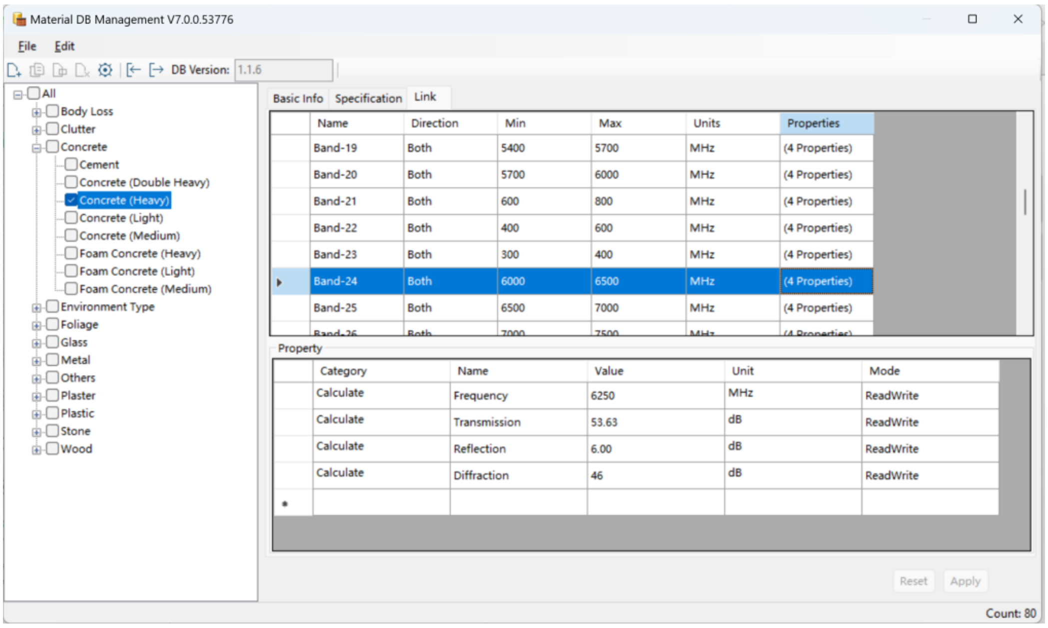


Figure 3: material loss configuration in Material Database

2.2 Environmental parameters calibration

Except the material loss, the environmental parameters, such as path loss constant and exponent parameters, terrain diffraction parameter, need to be calibrated based on the signal measurement. But different scenarios would have the different parameters. In this simulation, two scenarios are measured, and data are imported into simulation platform for calculation.

2.2.1 Measurement in campus scenario

The open space campus scenario in Durham University is measured for verifying the path loss parameters, as show in Figure 4, where two types of measurements are done, i.e. line of sight (LOS) and non-line of sight (NLOS), as shown in Figure 5. The signal reflection on the external walls would cause the additional loss, so outdoor non-line of sight measurement can verify the reflection loss at the same time.

Figure 4: campus open space scenario

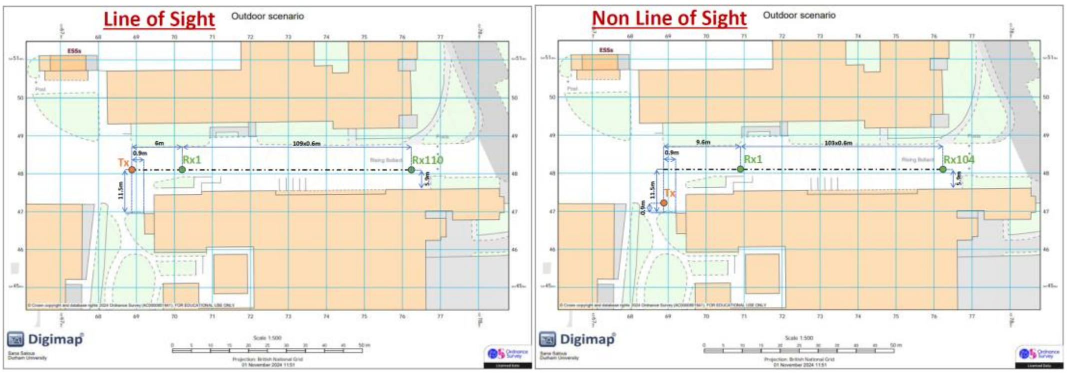


Figure 5: two types of measurement

Table 2 lists the measurement results for LOS and NLOS scenarios, which are imported into WP2 simulation platform for verifying and calibrating the propagation model.

Table 2: measurement data

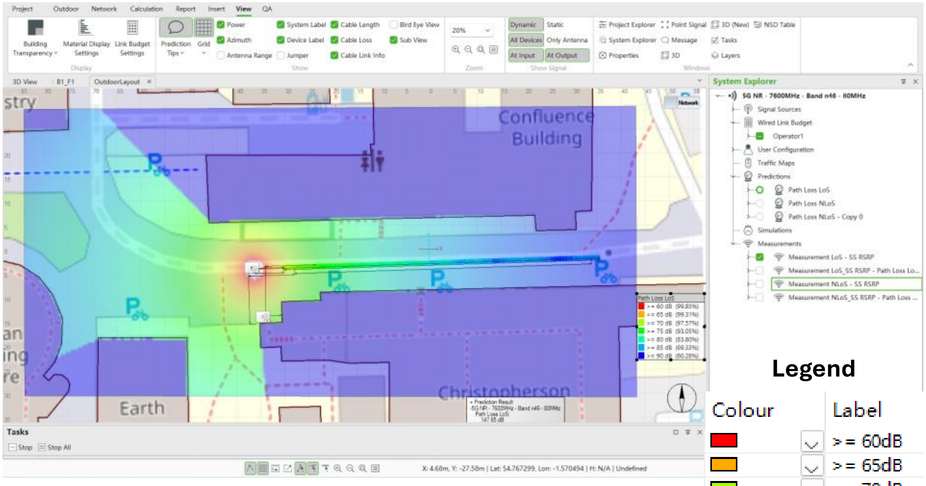
Environment category:	Outdoor
Frequency (GHz):	7.6
Bandwidth (GHz):	1
Distance_Tx-Rx (m)	Path loss (dB)
6.14	69.93
6.73	69.34
7.32	70.02
7.91	70.11
8.50	70.76
9.09	71.47
9.69	72.12
10.28	72.56
10.88	72.32
11.47	71.40
12.07	72.30

(a) LOS

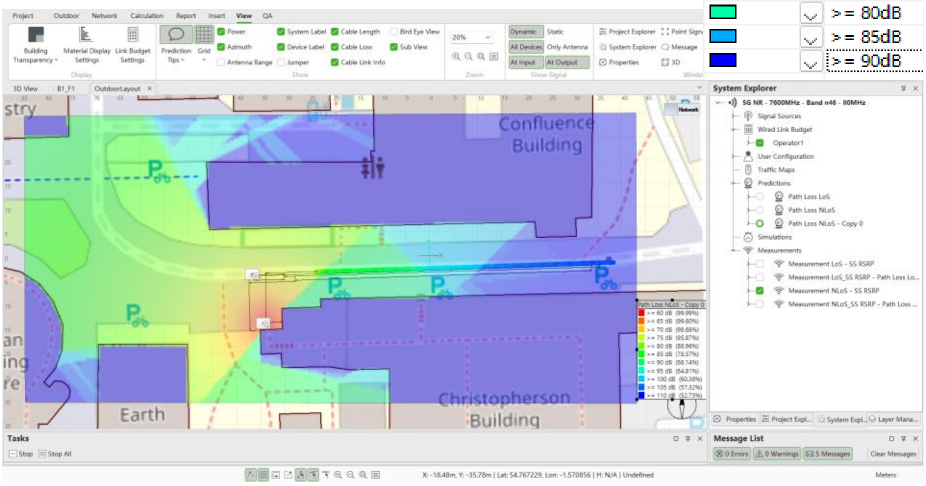
Environment category:	Outdoor
Frequency (GHz):	7.6
Bandwidth (GHz):	1
Distance_Tx-Rx (m)	Path loss (dB)
14.36	83.64
14.77	82.62
15.19	83.60
15.62	85.99
16.06	86.63
16.52	81.16
16.98	86.93
17.45	83.80
17.93	82.10
18.41	86.01
18.91	85.46

(b) NLOS

After importing these data into simulation platform, we simulate the signal coverage, and compare the simulation results with the measurement results, as shown in Figure 6. From the heat map, simulation results can match the measurement results almost. Figure 7 shows the error statistic results between simulation and measurement for two types of scenarios. For LOS scenario, the average and standard deviation of error between simulation and measurement are -2.32dB and 1.771dB respectively, and for NLOS scenario, the average and standard deviation of error are -2.113dB and 3.328dB respectively, which means that the default path loss parameters in the simulation platform can match that in the open space environment. So we can use the default path loss parameters to simulate the open space environment or rural environments.

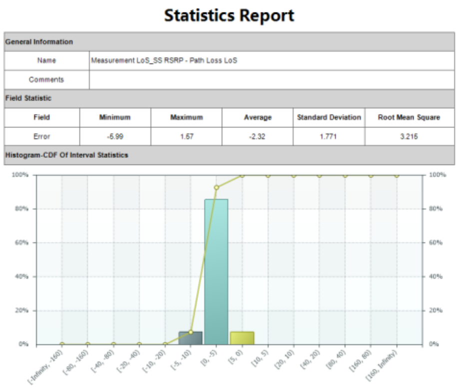


(a) LOS

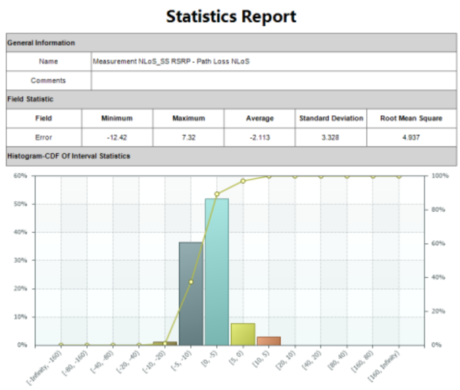


(b) NLOS

Figure 6: simulation and measurement results



(a) LOS

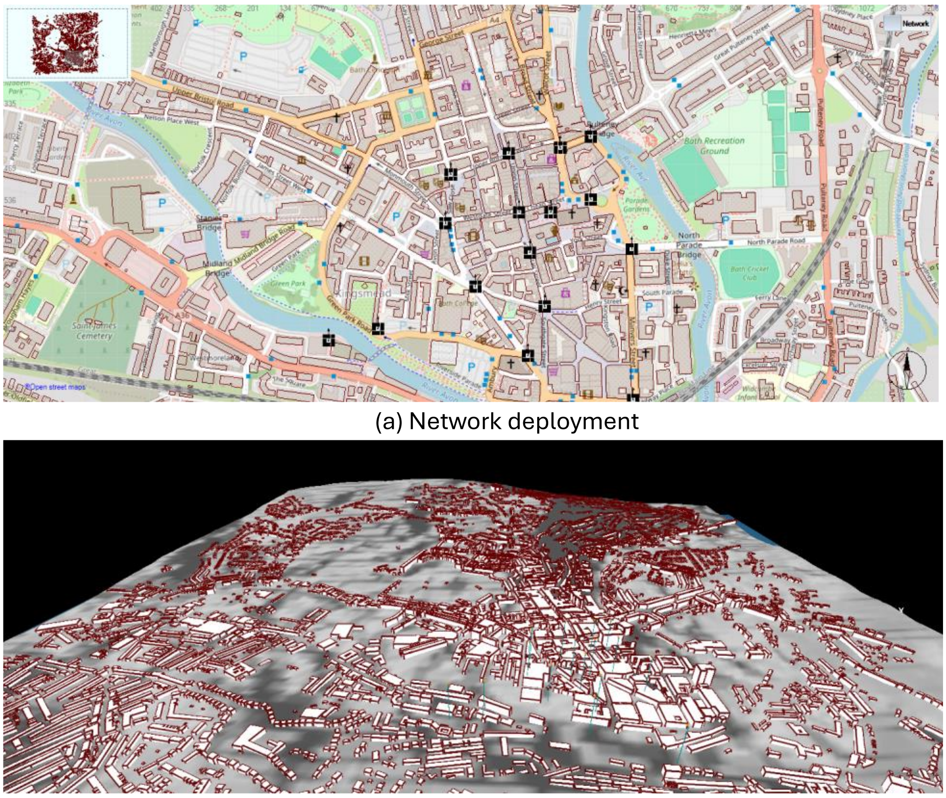


(b) NLOS

Figure 7: statistic results of simulation and measurement results

2.2.2 Measurement in urban scenario

The urban scenario in Bath is measured for verifying the path loss parameters in the urban environment, as show in Figure 8, where 16 Pico cells are deployed in the urban area, and the omnidirectional antennas are mounted on street lampposts with 4-meter heights.



(a) Network deployment

(b) 3D view

Figure 8: scenario for urban environment

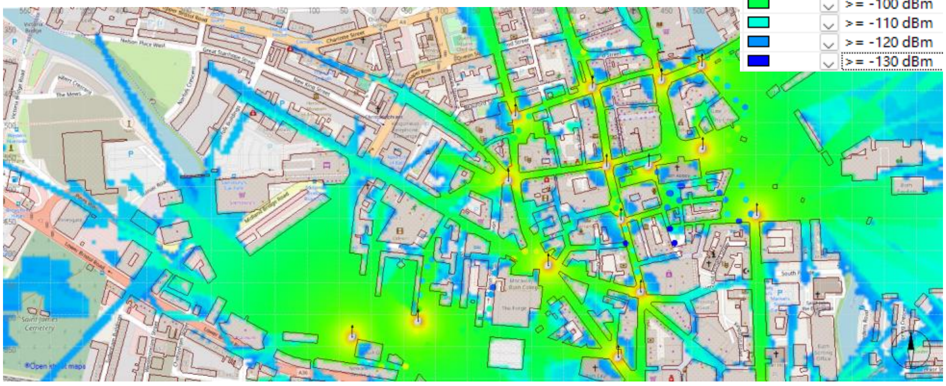
The network parameters are shown in Table 3.

Table 3: network parameters

Parameters	Configuration
Wireless System	5G NR
Carrier Frequency	3.7 GHz Band n77
Channel Bandwidth	100 MHz
Cell Tx Power per Port	37 dBm (Pico Cells)
MIMO	4x4
Antenna Gain	6 dB Omni-directional
Cell EIRP	49 dBm

But based on the information from WP1, in practice the Tx power is likely to be less than 37dBm from the measurement results, because the LOS distance between Tx and Rx is less than 150m. So, when comparing the results between simulation and measurement results, the Tx powers are adjusted to minimize the error.

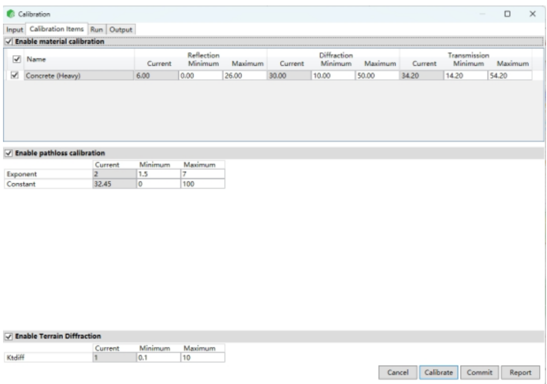
(a) Measurement results



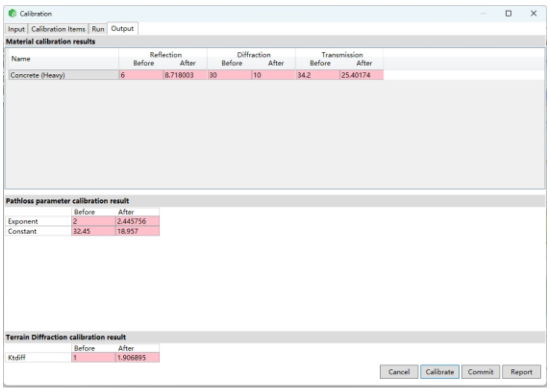
(b) Simulation results

Figure 9: measurement and simulation results

Based on the default configuration of propagation engine in simulation platform, there are a large error between simulation and measurement, as shown in Figure 9, so ray-tracing model calibration is done to calibrate the path loss parameters, as shown in Figure 10.



(a) Path loss parameters before calibration

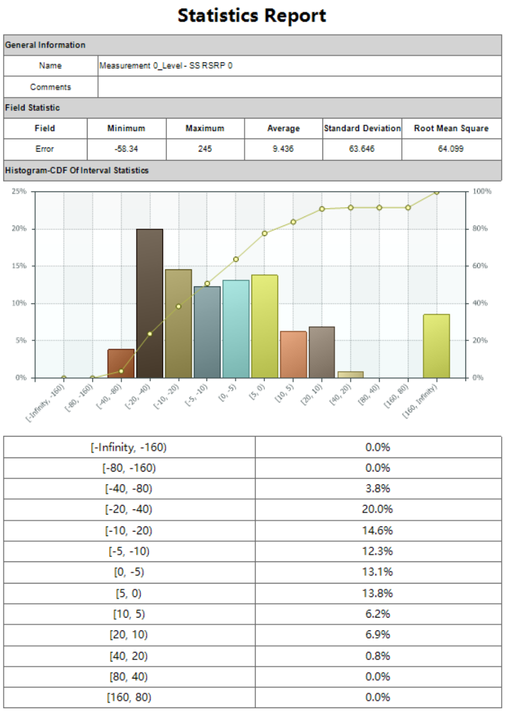


(b) Path loss parameters after calibration

Figure 10: propagation engine calibration

Figure 11 shows the error statistic between simulation and measurement before/after calibration. From statistic results, the average and standard deviation are improved significantly after calibration, i.e. the average error is improved for 9.436dB to -1.847dB, and standard deviation is improved from 64.099dB to

13.049dB, which means the path loss parameters after calibration can more match the real urban propagation environment, so the parameters can be used to simulate the following urban scenario, and output the accurate performance.



Statistics Report

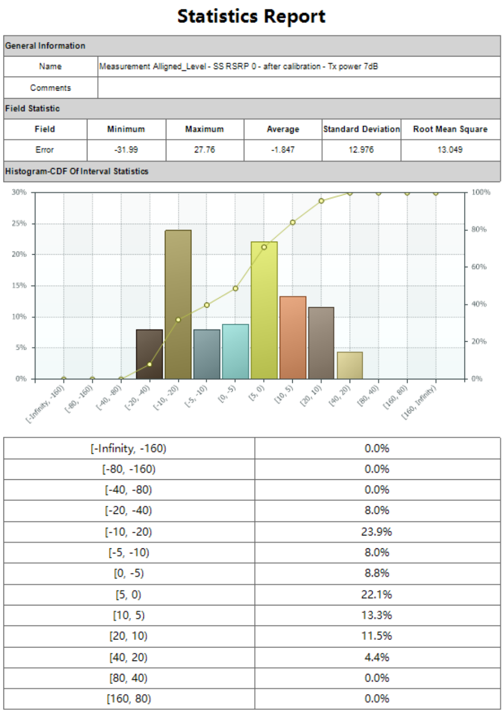
General Information	
Name	Measurement 0_Level - SS RSRP 0
Comments	

Field	Minimum	Maximum	Average	Standard Deviation	Root Mean Square
Error	-58.34	245	9.436	63.646	64.099

Histogram-CDF Of Interval Statistics

[-Infinity, -160)	0.0%
[-80, -160)	0.0%
[-40, -80)	3.8%
[-20, -40)	20.0%
[-10, -20)	14.6%
[-5, -10)	12.3%
[0, -5)	13.1%
[5, 0)	13.8%
[10, 5)	6.2%
[20, 10)	6.9%
[40, 20)	0.8%
[80, 40)	0.0%
[160, 80)	0.0%

(a) Error statistic before calibration



Statistics Report

General Information	
Name	Measurement Alligned_Level - SS RSRP 0 - after calibration - Tx power 7dB
Comments	

Field	Minimum	Maximum	Average	Standard Deviation	Root Mean Square
Error	-31.99	27.76	-1.847	12.976	13.049

Histogram-CDF Of Interval Statistics

[-Infinity, -160)	0.0%
[-80, -160)	0.0%
[-40, -80)	0.0%
[-20, -40)	8.0%
[-10, -20)	23.9%
[-5, -10)	8.0%
[0, -5)	8.8%
[5, 0)	22.1%
[10, 5)	13.3%
[20, 10)	11.5%
[40, 20)	4.4%
[80, 40)	0.0%
[160, 80)	0.0%

(b) Error statistic after calibration

Figure 11: error statistic before/after calibration

3. 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.

3.1 Indoor/outdoor split mechanism

For indoor and outdoor service scenarios, indoor/outdoor split mechanism uses building entry losses to help isolate indoor and outdoor two services, and enable both services to operate in the same geographical areas. At the same time, adjusting the power of mobile base stations, to some degree, may help to limit the overlap area in the building, and then reduce the interference further due to spectrum sharing.

The mobile industry has indicated that they expect upper 6 GHz will be needed to add extra capacity. Conversely, Wi-Fi networks are predominantly deployed indoors in almost every home and office, and Upper 6 GHz is especially needed to provide Wi-Fi capacity in the busiest indoor. So, we expect to analyse the sharing mechanism for upper 6 GHz band by mobile and Wi-Fi. Ofcom has published a document to discuss the indoor/outdoor split mechanism between outdoor mobile and indoor Wi-Fi network [1]. The mechanism would reduce the need for sharing spectrum resources in time or frequency between mobile and Wi-Fi at those overlap locations.

But we need to better understand the trade-off between the simplicity of mechanisms that might be needed by both mobile and Wi-Fi, and the impact that constraining mobile power may have on the usability of the spectrum by mobile.

In order to evaluate the impact of mobile power, we simulate an indoor/outdoor dense urban scenario with upper 6GHz spectrum sharing, as shown in Figure 12 and Table 4. The study area is central London, covering approximately 8.5 km^2 of high-rise building with flat terrain. Building losses are categorized as high-loss concrete wall and double-glazing glass. Regarding traffic, 70% traffic occurs indoors and 30% traffic occurs outdoors, and buildings exceeding 50.00 m^2 in floor area are modelled to deploy the indoor Wi-Fi systems.

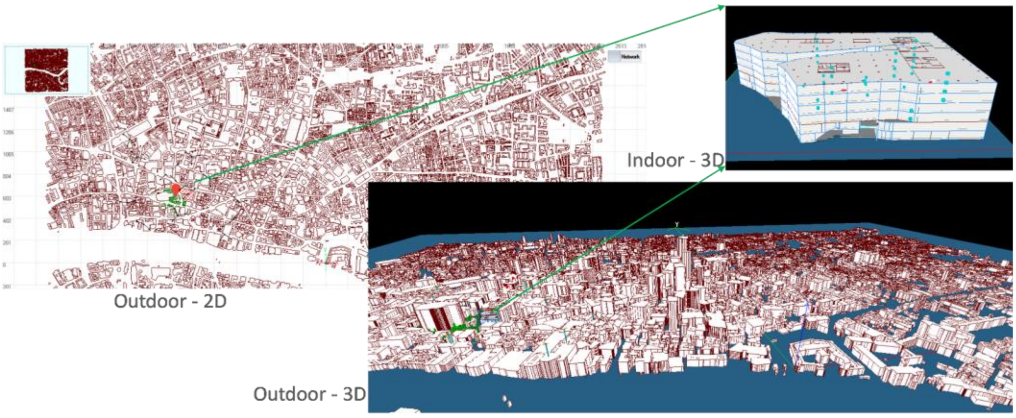


Figure 12: indoor/outdoor dense urban scenario

Table 4: parameters configuration

Parameters	Configuration
Wireless System	5G NR
Carrier Frequency	Upper 6 GHz
Channel Bandwidth	100 MHz
Cell Tx Power per Port	31dBm to 67dBm
MIMO	4x4
Antenna Gain	15.88dB directional
Cell EIRP	52.88 dBm to 88.88 dBm

When adjusting the outdoor macro cells' Tx power per port from 67dBm to 43dBm, the signal from outdoor to indoor can be isolated, and the smaller indoor overlap reduces the interference due to spectrum sharing, as shown in Figure 13.

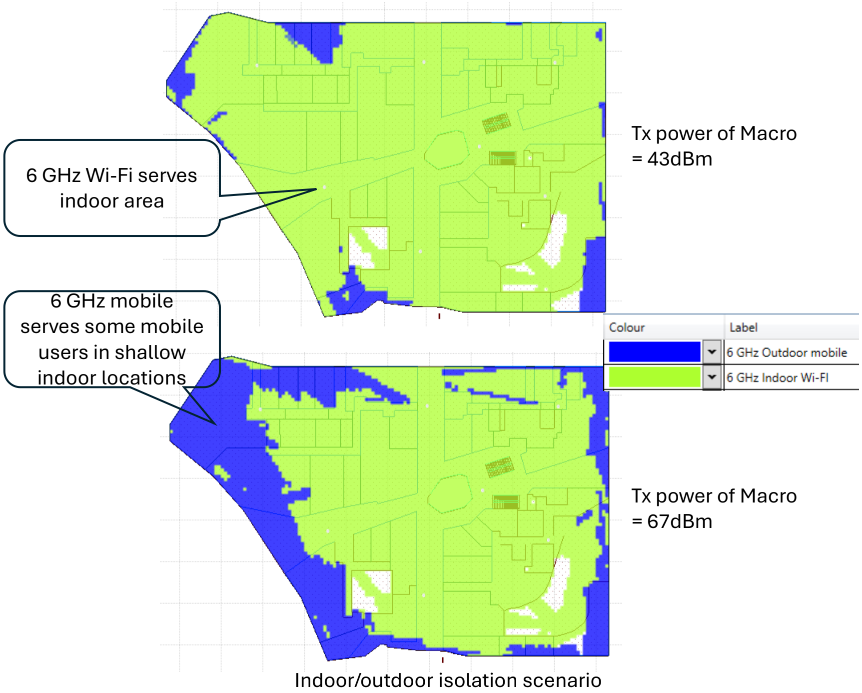


Figure 13: overlap area from outdoor to indoor

Table 5 lists the simulation performances with different Tx powers for indoor/outdoor split mechanism. From this simulation results, upper 6GHz mobile network average throughput (TP) for outdoor mobile users and indoor Wi-Fi users degrades by 25.6%, and cell-edge TP degrades by 87.1% when adjusting Tx power from 31 to 67dBm, but the coverage improves by 8.9%, which means reducing Tx power would impact the coverage, and new base stations need to be deployed to compensate the coverage drop, but the cost increases accordingly. Therefore, for indoor/outdoor split sharing mechanism, BS Tx power between the range 43dBm to 49dBm is the minimum value, i.e. 64.88dBm to 70.88dBm EIRP.

Table 5: Overall DL coverage and throughput with Tx power adjustment

Macro TX power per Port (dBm)	Coverage (%)	DL average user TP (Mbps)	Cell edge user TP (Mbps)
31	87.3	40.3	7.8
37	90.1	38.9	4.4
43	92.2	37.6	1.8
49	93.1	35.3	1.7
55	93.8	32.9	1.3
61	94.6	31.1	1.1
67	95.1	30.2	1.0

3.2 Spectrum sensing mechanism

Spectrum sensing technique is another spectrum sharing mechanism for the system pairs [1], 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, as shown in Figure 14.

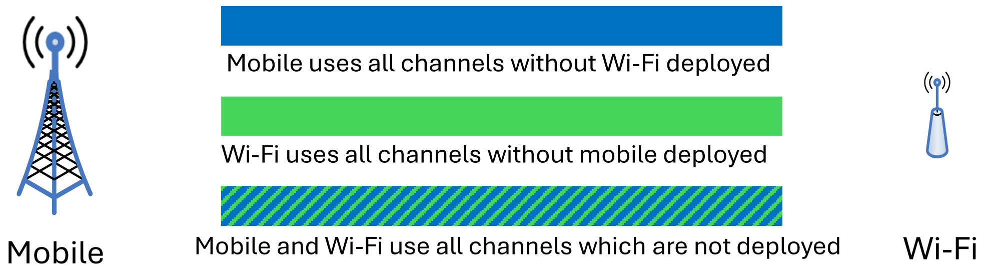
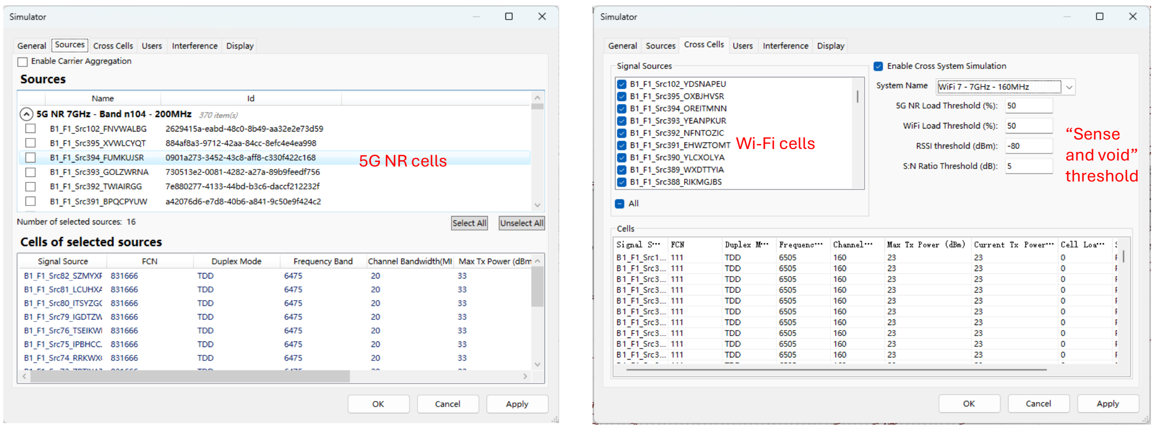


Figure 14: spectrum sensing mechanism

“Sense and avoid” techniques for each system are modelled in the simulation platform, as shown in Figure 15, 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 and sensing configuration

Figure 15: spectrum sensing configuration in the simulation

4 Simulation performance of solutions

This section simulates the performances with the sharing mechanisms, and output the simulation data into WP3 for the economic analysis.

4.1 Use case

WP2 would simulate five system pairs and multiple use cases, as developed by the consortium, for economic analysis in WP3, as shown in Table 6.

Table 6: use case introduction

Pairs	Technical modelling	Shared spectrum	Use cases	Sharing mechanisms
Mobile and Wi-Fi	WP2	Upper 6 GHz (For rural, n77 band is used)	High density public events (e.g. football matches) – Stadium	Spectrum sensing
			Sharing frequencies for Wi-Fi/mobile indoor/outdoor – High density urban – Dense urban – Urban – Rural	Indoor/Outdoor split
Private networks	WP2	n77 Band 3.7GHz	Low density urban	Spectrum sensing
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
Scientific stations and Mobile	WP2	Upper 6 GHz	Use of mobile network in the vicinity of radio-astronomy receivers	Geographic separation

4.2 Simulation performance of mobile and Wi-Fi

Four scenarios for spectrum sharing between mobile and Wi-Fi pair are simulated, as shown in Table 7, where target data rate is fixed, and the same technology, such as 5G NR, is used, WP2 would simulate the number of base stations, small cells, and Wi-Fi APs, and output the CAPEX and OPEX for economic analysis, where base station is an outdoor macro cell.

Table 7: scenario introduction [2]

Scenario	Assumptions

Existing Provision (Scenario 0)	**Mimic current mobile and Wi-Fi network provision for each use case to understand what the costs (CAPEX and OPEX) of delivering the current service are.** - Mimic existing Wi-Fi network provision (2.4/5 GHz) to achieve current speeds achieved for 100% indoor Wi-Fi users. - Mimic existing mobile network provision (4G/5G) to achieve current speeds for the outdoor mobile users.
Non-Upper 6 GHz Additional Provision (Scenario 1)	**Simulate mobile and Wi-Fi networks that meet their respective demand target parameters using their current spectrum allocation: n78 band for mobile & 2.4/5 GHz for Wi-Fi.** - Deploy additional indoor Wi-Fi infrastructure in order for 100% indoor Wi-Fi users to achieve our target speeds using 2.4 GHz/5 GHz Wi-Fi - Deploy additional outdoor mobile infrastructure for the outdoor mobile users to achieve our target speeds from current 4G/5G spectrum bands.
Mobile Only Upper 6 GHz, Wi-Fi Unchanged (Scenario 2)	**Simulate an Upper 6 GHz mobile Network (ideally up to 700 MHz) that meets the demand target parameters for both indoor and outdoor mobile users. Wi-Fi only uses its current spectrum allocation to meet the demand target parameters.** - Outdoor mobile users (30% of all mobile users) would be served by outdoor mobile 6 GHz deployment meeting our specified target speeds. - For the indoor mobile users (70% of all mobile users), Indoor small cell upper 6 GHz mobile deployment (at lower cost than outdoor deployment) would be used to meet our target speeds for all indoor mobile users. - The 100% Wi-Fi indoor users would be served by existing (2.4/5 GHz) Wi-Fi bands meeting our target speeds.
Wi-Fi Only Upper 6 GHz, Mobile Unchanged (Scenario 3)	**Simulate an Upper 6 GHz Wi-Fi network that meets the demand target parameters for all Wi-Fi users (who are assumed to all be indoor). Mobile only uses its current 4G/5G spectrum allocation to meet the demand target parameters.** - 100% Wi-Fi indoor users would be served by 6 GHz Wi-Fi indoor deployment meeting our target speeds. - For the mobile case, mobile users would have to use existing 4G/5G bands.
Spectrum Sharing of Upper 6 GHz (Scenario 4)	**Simulate mobile and Wi-Fi networks that share the Upper 6 GHz band based on indoor/outdoor split sharing mechanisms that meet the demand target parameters for all Wi-Fi users and all outdoor mobile users.** - The outdoor mobile users (30% of all mobile users) would be served by outdoor mobile 6 GHz deployment meeting our target speeds.

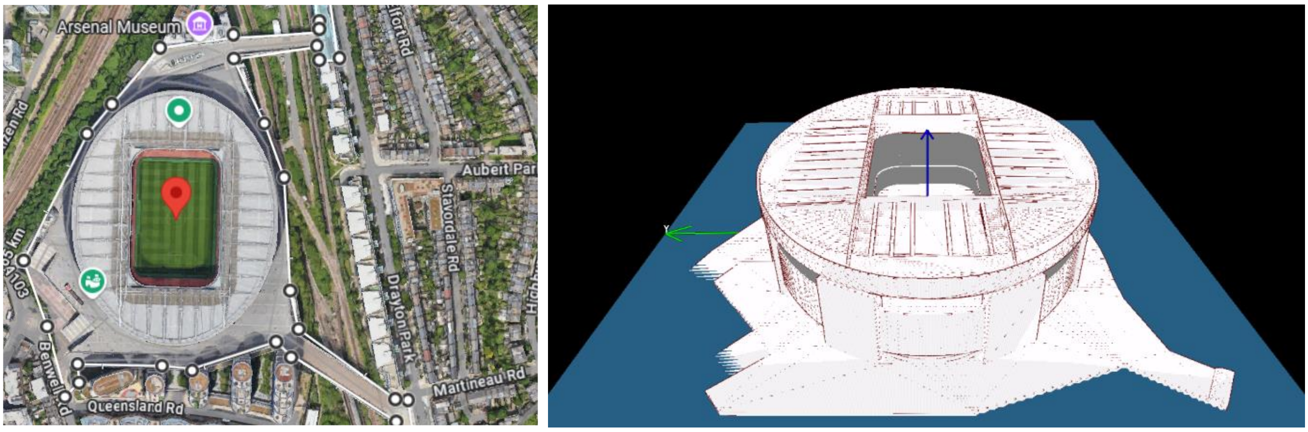
	- The 100% Wi-Fi indoor users would be served by 6 GHz Wi-Fi indoor deployment meeting our target speeds.

4.2.1 Use case 1 – Stadium

The high-density public events (e.g. football matches) is simulated to evaluate the peak requirements for the entire events duration.

The study case is Emirates Stadium, which tests whether it is possible to alleviate network congestion by making use of Wi-Fi in high traffic areas while allowing for licensed mobile use elsewhere. Figure 16 shows the modelling in the simulation, and Table 8 shows the mobile and Wi-Fi demand parameters.

This use case is characterised by a very large number of connected devices (thousands to hundreds of thousands) in a relatively small area. Line of sight issues and (temporary) high urban densities present short-term spectrum bottlenecks. Given the large number of devices requiring data intensive applications, cumulative bandwidth will be high. These devices will primarily be mobile phones, so users (consumers) can be considered mobile, although other mobile 'smart' devices may also be addressable in future. Data intensity of these applications is expected to increase significantly over time.



(a) Emirates Stadium

(b) 3D view in simulation

Figure 16: Emirates Stadium case

Table 8: mobile and Wi-Fi demand parameters

Parameter	Mobile/Wi-Fi
Population (P) (Total Stadium Capacity)	60,700
Area (A) (Concourse + Stadium)	0.0688 km2
Population Density (PD)	882,267 People/km2

Activity Factor (AF)	40%
Total Offload Factor (OF) (= High Band + Indoor Mid Band)	38% (=28% + 10%)
Peak Active Users (U) (= P * AF * (1 – OF))	**15,054 Users**
Peak Active User Density (UD) (= PD * AF * (1 – OF))	**281,802 Users/km2**
User Experienced DL Rate	25 Mbps
User Experienced UL Rate	50 Mbps

Table 9 presents the main network parameters used in this study. Parameters for both the existing 5G and the Upper 6 GHz band are provided for mobile, and existing 5 GHz and upper 6 GHz for Wi-Fi, as the 5G mobile and 5 GHz Wi-Fi results are given for reference.

Table 9: network parameters

Parameters	Configuration	
Wireless System	5G NR	Wi-Fi
Carrier Frequency	n78 3.5 GHz/Upper 6 GHz	Wi-Fi 5 GHz/Upper 6 GHz
Channel Bandwidth	80 MHz/200MHz	160MHz
Cell Tx Power per Port	33dBm	23dBm
Antenna Gain	12dBi/26-degree beam width	12dBi/26-degree beam width
Duplex	TDD (DL: 40%)	TDD
MIMO	8x8	8x8
Cell EIRP	54 dBm	44 dBm

4.2.1.1 Coverage performance

Figure 17 presents the coverage performance. From the figure, the 99.97% area is covered if the compliance is -95dBm@SS RSRP for 5G NR, which means the network design meets the coverage requirements.

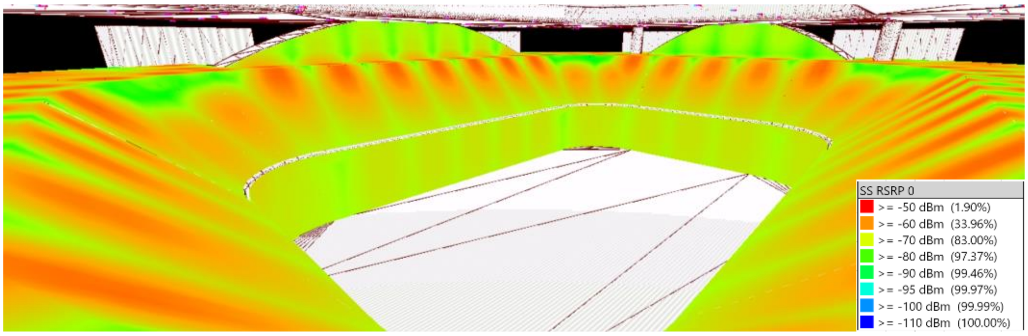


Figure 17: coverage performance

4.2.1.2 Performance of Scenario 0

Table 10 shows the network performance of mobile for scenario 0. From the table, based on the UE configuration and data rate requirements, 57 mobile base stations need to be deployed to cover the seating area and concourse area.

Table 10: network performance of mobile

(1)System Overview						
System Type	5G NR - 3500MHz - Band n78 - 80MHz					
Frequency	3500 MHz					
Bandwidth	80 MHz					
No. of Cell	57					
No. of User	15071					
Service Type	8*8 MIMO					
(2)System Voice Service Results						
	Downlink Voice User			**Uplink Voice User**		
Voice User	0.00			0.00		
(3)System Data Service Results						
	System Downlink Throughput(Mbps)	**User Downlink Average Throughput(Mbps)**	**User Downlink Edge Throughput(Mbps)**	**System Uplink Throughput(Mbps)**	**User Uplink Average Throughput(Mbps)**	**User Uplink Edge Throughput(Mbps)**
System	36494.28	2.421	0.209	76628.08	5.084	0.233
(4)Traffic Results						
8*8 MIMO	36494.28	2.421	0.209	76628.08	5.084	0.233
(5)User Results						

	Downlink	Uplink
Unserved User Ratio	0.00%	0.00%
Connected User Ratio	0.00%	0.00%
Scheduled User Ratio	100.00%	100.00%

Table 11 shows the network performance of Wi-Fi for scenario 0. From the table, 144 Wi-Fi APs need to be deployed to cover the seating area and concourse area.

Table 11: network performance of Wi-Fi

(1)System Overview						
System Type	Wi-Fi 802.11ax - 5GHz - 80MHz					
Frequency	5000 MHz					
Bandwidth	80 MHz					
No. of Cell	144					
No. of User	15048					
Service Type	8x8 MIMO					
(2)System Voice Service Results						
	Downlink Voice User			**Uplink Voice User**		
Voice User	0.00			0.00		
(3)System Data Service Results						
	System Downlink Throughput(Mbps)	**User Downlink Average Throughput(Mbps)**	**User Downlink Edge Throughput(Mbps)**	**System Uplink Throughput(Mbps)**	**User Uplink Average Throughput(Mbps)**	**User Uplink Edge Throughput(Mbps)**
System	62460.87	4.34	1.94	146221.77	10.16	2.901
(4)Traffic Results						
8x8 MIMO	62460.87	4.34	1.94	62460.87	10.16	2.901
(5)User Results						
	Downlink			**Uplink**		
Unserved User Ratio	0.01%			0.01%		
Connected User Ratio	4.35%			4.35%		
Scheduled User Ratio	95.64%			95.64%		

Once the number of mobile base stations and Wi-Fi APs are simulated to determine, the CAPEX and OPEX can be calculated based on the following assumptions:

CAPEX

1. For base station deployment, we can estimate the cost of equipment and construction
    1. Radio: £10,000
    2. Ancillaries (PSU, antennas, feeders, 5G core, routers etc): £2000
    3. Installation: £6000 - can vary considerably depending on location and covers civil engineering work and operator management costs.
    4. Backhaul: Variable - ranging from £0 (install bundled into the OPEX cost) to very expensive. At present we still have sites with no fibre connectivity. Installation of a microwave last mile can be expensive depending on location, and as an example we had a £20,000 quote (double microwave link) for an installation in the UK. The cost reflects the remoteness of the area and the difficult terrain.
2. For small cell deployments, we can estimate the cost of equipment and construction
    1. Small cell: £5000
    2. Installation: £3000
3. For Wi-Fi AP deployments, we can estimate the cost of equipment and construction
    1. Wi-Fi AP (all cost of equipment and installation): £5000

OPEX

1. Fibre backhauls: £5,000 - £10,000 depending on customer requirement (1GBps - 10GBps)
2. Support and maintenance; Estimate 40% of CAPEX costs to cover break fix, back-end systems, customer support etc.
3. Power costs: we build them into contracts and the customer pays. However, a typical single cell runs at a few 100 W, albeit 7X24.
4. Hardware replacement and software upgrade

4.2.1.3 Performance of Scenario 1

Table 12 shows the network performance of mobile for scenario 1. From the table, based on the UE configuration and data rate requirements in Table 8, 370 mobile base stations are deployed to cover the seating area and concourse area if existing 5G spectrum is used.

Table 12: network performance of mobile

(1)System Overview	
System Type	5G NR - 3500MHz - Band n78 - 80MHz
Frequency	3500 MHz
Bandwidth	80 MHz

No. of Cell	370					
No. of User	15068					
Service Type	8*8 MIMO					
(2)System Voice Service Results						
	Downlink Voice User			**Uplink Voice User**		
Voice User	0.00			0.00		
(3)System Data Service Results						
	System Downlink Throughput(Mbps)	**User Downlink Average Throughput(Mbps)**	**User Downlink Edge Throughput(Mbps)**	**System Uplink Throughput(Mbps)**	**User Uplink Average Throughput(Mbps)**	**User Uplink Edge Throughput(Mbps)**
System	398854.8	26.47	10.226	788596.4	52.336	41.855
(4)Traffic Results						
8*8 MIMO	398854.8	26.47	10.226	788596.4	52.336	41.855
(5)User Results						
	Downlink			**Uplink**		
Unserved User Ratio	0.00%			0.00%		
Connected User Ratio	0.00%			0.00%		
Scheduled User Ratio	100.00%			100.00%		

Table 13 shows the network performance of Wi-Fi for scenario 1. From the table, 370 Wi-Fi APs are deployed to cover the seating area and concourse area.

Table 13: network performance of Wi-Fi

(1)System Overview		
System Type	Wi-Fi 802.11ax - 5GHz - 80MHz	
Frequency	5000 MHz	
Bandwidth	80 MHz	
No. of Cell	370	
No. of User	15051	
Service Type	8*8 MIMO	
(2)System Voice Service Results		
	Downlink Voice User	**Uplink Voice User**

Voice User	0.00			0.00		
(3)System Data Service Results						
	System Downlink Throughput(Mbps)	**User Downlink Average Throughput(Mbps)**	**User Downlink Edge Throughput(Mbps)**	**System Uplink Throughput(Mbps)**	**User Uplink Average Throughput(Mbps)**	**User Uplink Edge Throughput(Mbps)**
System	361958.9	24.596	12.223	754664.3	51.282	6.862
(4)Traffic Results						
8*8 MIMO	361958.9	24.596	12.223	754664.3	51.282	6.862
(5)User Results						
	Downlink			**Uplink**		
Unserved User Ratio	0.00%			0.00%		
Connected User Ratio	2.23%			2.23%		
Scheduled User Ratio	97.77%			97.77%		

4.2.1.4 Performance of Scenario 2

Table 14 shows the network performance of mobile only for scenario 2. From the table, based on the UE configuration and data rate requirements in Table 8, 196 mobile base stations are deployed to cover the seating area and concourse area if upper 6 GHz spectrum is used.

Table 14: network performance of mobile only

(1)System Overview						
System Type	5G NR - 7000MHz - Band104 - 200MHz					
Frequency	7000 MHz					
Bandwidth	200 MHz					
No. of Cell	196					
No. of User	15039					
Service Type	8x8 MIMO					
(2)System Voice Service Results						
	Downlink Voice User			**Uplink Voice User**		
Voice User	0.00			0.00		
(3)System Data Service Results						
	System Downlink	**User Downlink Average**	**User Downlink Edge**	**System Uplink Throughput(Mbps)**	**User Uplink Average**	**User Uplink Edge**

	Throughput(Mbps)	Throughput(Mbps)	Throughput(Mbps)		Throughput(Mbps)	Throughput(Mbps)
System	406355.4	27.02	23.419	868417.8	57.864	66.244
(4)Traffic Results						
8x8 MIMO	406355.4	27.02	23.419	868417.8	57.864	66.244
(5)User Results						
	Downlink			**Uplink**		
Unserved User Ratio	0.00%			0.00%		
Connected User Ratio	0.00%			0.21%		
Scheduled User Ratio	100.00%			99.79%		

4.2.1.5 Performance of Scenario 3

Table 15 shows the network performance of Wi-Fi only for scenario 3. From the table, based on the UE configuration and data rate requirements Table 8, 252 Wi-Fi APs are deployed to cover the seating area and concourse area if upper 6 GHz spectrum is used.

Table 15: network performance of Wi-Fi only

(1)System Overview						
System Type	Wi-Fi 802.11be - 7GHz - 160MHz					
Frequency	7000 MHz					
Bandwidth	160 MHz					
No. of Cell	252					
No. of User	15049					
Service Type	8*8 MIMO					
(2)System Voice Service Results						
	Downlink Voice User			**Uplink Voice User**		
Voice User	0.00			0.00		
(3)System Data Service Results						
	System Downlink Throughput(Mbps)	**User Downlink Average Throughput(Mbps)**	**User Downlink Edge Throughput(Mbps)**	**System Uplink Throughput(Mbps)**	**User Uplink Average Throughput(Mbps)**	**User Uplink Edge Throughput(Mbps)**
System	389422.9	25.877	20.558	748661.5	50.791	30.619
(4)Traffic Results						

8*8 MIMO	389422.9	25.877	20.558	748661.5	50.791	30.619
(5)User Results						
	Downlink			**Uplink**		
Unserved User Ratio	0.00%			0.00%		
Connected User Ratio	1.05%			1.05%		
Scheduled User Ratio	98.95%			98.95%		

4.2.1.6 Performance of Scenario 4

Table 16 shows the network performance of spectrum sharing for scenario 4, where small cell means the Wi-Fi AP. From the table, based on the UE configuration and data rate requirements in Table 8, total 206 mobile base stations and Wi-Fi APs are deployed to cover the seating area and concourse area if upper 6 GHz spectrum is used, where the spectrum sensing threshold is set into -80dBm.

Table 16: network performance of spectrum sharing

(1)System Overview						
System Type	5G NR - 7000MHz - Band104 - 200MHz					
Frequency	7000 MHz					
Bandwidth	200 MHz					
No. of Cell	206					
No. of User	15040					
Service Type	8x8 MIMO					
(2)System Voice Service Results						
	Downlink Voice User			**Uplink Voice User**		
Voice User	0.00			0.00		
(3)System Data Service Results						
	System Downlink Throughput(Mbps)	**User Downlink Average Throughput(Mbps)**	**User Downlink Edge Throughput(Mbps)**	**System Uplink Throughput(Mbps)**	**User Uplink Average Throughput(Mbps)**	**User Uplink Edge Throughput(Mbps)**
System	388841.43	25.853	11.507	786183.12	52.272	30.478
Small Cell	358008.57	25.808	15.343	724173.88	52.204	24.382
Macro Cell	30832.86	26.398	7.061	62009.24	53.09	4.669
(4)Traffic Results						
8x8 MIMO	388841.43	25.853	11.507	786183.12	52.272	30.478

(5)User Results		
	Downlink	**Uplink**
Unserved User Ratio	0.00%	0.00%
Connecte d User Ratio	0.00%	0.00%
Scheduled User Ratio	100.00%	100.00%

Based on the simulation, the number of mobile base stations or Wi-Fi APs can be summarized, as shown in Table 17. From this table, Scenario 0 to 4 are defined in Table 7, when fixed the data rate for the future rate requirement, for example in 2035, and based on the estimation of CAPEX and OPEX in Section 4.2.1.2, spectrum sharing solution, i.e. Scenario 4, will reduce network deployment costs to achieve desired coverage and capacity because only 8 base stations and 198 Wi-Fi APs are deployed, the cost is lower than the cost of 370 base stations or 370 Wi-Fi APs in Scenario 1, or the cost of 196 base stations in Scenario 2, or the cost of 253 Wi-Fi APs in Scenario 3. WP3 will present how cost savings, or burdens for upper 6 GHz with spectrum sensing sharing mechanism and provide the accurate cost analysis for the stadium case.

Table 17: simulation summary for Scenario 0 to 4

	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
No. of Mobile BSs	57	370	196	-	8
No. of Wi-Fi APs	144	370	-	252	198

We must point out that the Wi-Fi simulation only consider 5GHz band is because WP3 suggestion most of the time Wi-Fi works in this band, and little traffic so far in lower 6 GHz, but Wi-Fi simulation should consider the lower 6 GHz band and multi-link operation in 2.4GHz/5GHz/6GHz three different bands simultaneously, like the carrier aggregation in mobile network, which will impact the cost of Wi-Fi only deployment and sharing deployment between Wi-Fi and mobile, especially in 2035, the Lower 6 GHz band will carry possibly the majority of Wi-Fi traffic. So

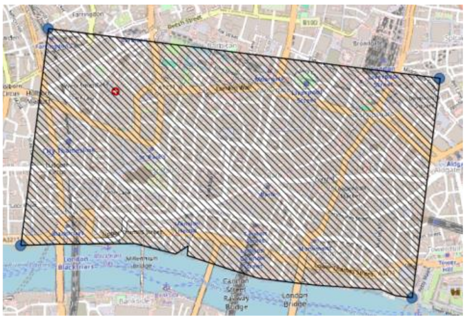
- When simulating the scenario 1, i.e. number of Wi-Fi APs based on currently spectrum allocation, because 6 GHz band can provide about 500MHz bandwidth, which can provide additional 3 channels if we still run 160MHz bandwidth in the simulation, there are total 6 channels. Theoretically, the interference will be decreased, and the number of Wi-Fi APs will be decreased corresponding.
- When simulating the scenario 1, 3 and 4, define the new offloading factor to lower 6GHz, like Table 8, where offload factor includes the high band and middle band, lower 6 GHz band should be considered, and additional offload factor should be added, here the factor can base on the total bandwidth available in lower 6 GHz vs the tiny amount in 2.4 GHz and the fragmentation in 5 GHz. when analyzing the cost and economics, the new offloading factor will be considered in the WP3 economic analysis report.

4.2.2 Use case 2 – High-density urban case

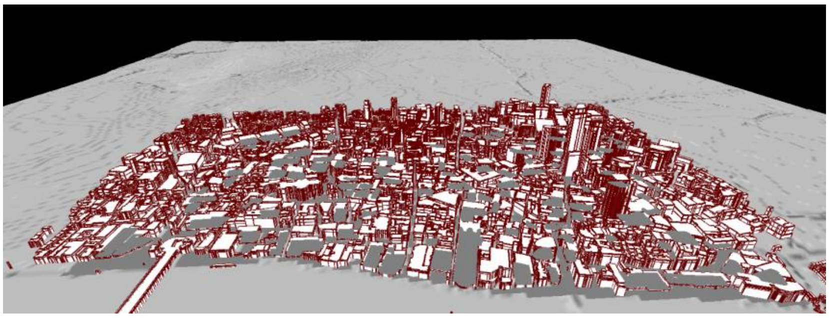
The high-density urban case would be simulated to evaluate the network requirement. The study case is London dense urban, which tests whether it is possible to alleviate network congestion by making use of

Wi-Fi in high traffic indoor areas while allowing for outdoor area. Figure 18 shows the modelling in the simulation, and Table 18 shows the mobile and Wi-Fi demand parameters.

This use case is characterised by numerous connected devices in a relatively small area. Urban canyons block line of sight and high user densities present spectrum bottlenecks. Given the large number of devices, cumulative bandwidth will be high. Today, these devices will primarily be mobile phones, so users (consumers) can be considered mobile, although some users will be fixed. Over the next decade, these users may extend to other 'mobile' applications such as connected and autonomous vehicles (CAVs).



(a) high-density urban



(b) 3D view in simulation

Figure 18: high-density urban case

Table 18: mobile and Wi-Fi demand parameters

Parameter	Mobile	Wi-Fi
Population (P) (Total Working Day Population)	469,067	469,067
Area (A) (Central London: North)	2.08 km2	2.08 km2
Population Density (PD)	225,513 People/km2	225,513 People/km2
Activity Factor (AF)	25%	20%
Total Offload Factor (OF) (= High Band + Indoor Mid Band)	38% (=28% + 10%)	-
Peak Active Users (U) (= P * AF * (1 – OF))	**72,705 Users**	-
Peak Active Outdoor Users (= 0.7 * U)	**50,894 Outdoor Users**	-

Peak Active Indoor Users **(= 0.3 * U)**	**21,811 Indoor Users**	**58,821 Users (100% Indoor)**
Peak Active User Density (UD) (= PD * AF * (1 – OF))	**34,955 Users/km2**	**28,279 Users/km2**
User Experienced DL Rate	100 Mbps	1,000 Mbps
User Experienced UL Rate	50 Mbps	500 Mbps

Table 19 presents the main network parameters used in this study. Parameters for both the existing 5G and the Upper 6 GHz band are provided for mobile, and existing 5 GHz and upper 6 GHz for Wi-Fi, as the 5G mobile and 5 GHz Wi-Fi results are given for reference.

Table 19: network parameters

Parameters	Configuration	
Wireless System	5G NR	Wi-Fi
Carrier Frequency	n78 3.5 GHz/Upper 6 GHz	Wi-Fi 5 GHz/Upper 6 GHz
Channel Bandwidth	80 MHz/200MHz	160MHz
Cell Tx Power per Port	46dBm	23dBm
Antenna Gain	15.88dBi/50-degree beam width	3dBi/Omni-directional
Duplex	TDD (DL: 60%)	TDD
MIMO	8x8	8x8
Cell EIRP	70.88 dBm	35 dBm

4.2.2.1 Coverage performance

Figure 19 presents the coverage performance. From the figure, the 94.63% area is covered if the compliance is -125dBm@SS RSRP for 5G NR, which means the network design meets the coverage requirements.

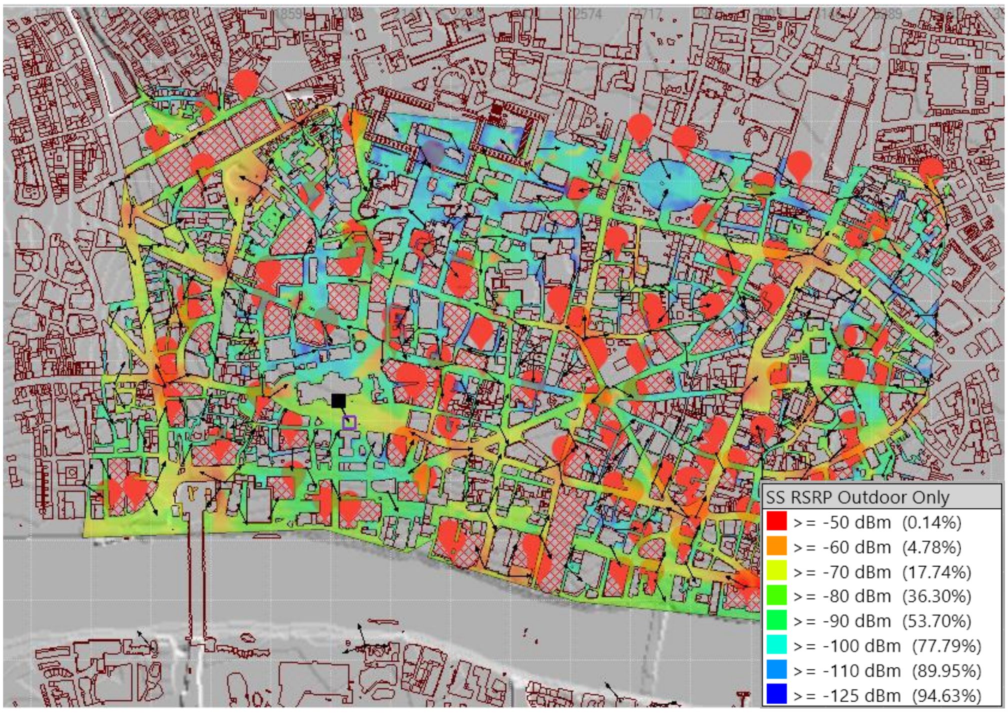


Figure 19: coverage performance

4.2.2.2 Performances of all Scenarios

Based on the simulation, the number of mobile base stations or Wi-Fi APs are summarized, as shown in Table 20. From this table, Scenario 0 to 4 are defined in Table 7, when fixed the data rate for the future rate requirement, for example in 2035, and based on the estimation of CAPEX and OPEX in Section 4.2.1.2, spectrum sharing solution, i.e. Scenario 4, will reduce network deployment costs to achieve desired coverage and capacity because only 729 base stations and 7807 Wi-Fi APs are deployed, the cost is lower than the cost of 1374 base stations and 18248 Wi-Fi APs in Scenario 1, or the cost of 1525 base stations/small cells and 18248 Wi-Fi APs in Scenario 2, or the cost of 1374 base stations and 7307 Wi-Fi APs in Scenario 3. WP3 will present how cost savings, or burdens for upper 6 GHz with spectrum sensing sharing mechanism and provide the accurate cost analysis for the high-density urban case.

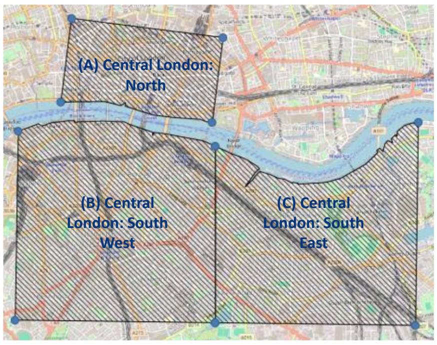
Table 20: summary of simulation

	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
No. of Mobile BSs	189	1374	1525	1374	729
No. of Wi-Fi APs	837	18248	18248	7307	7807

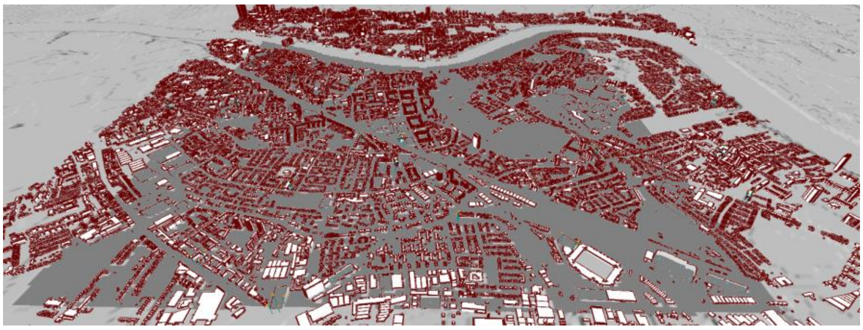
4.2.3 Use case 3 – Dense urban case

The dense urban case would be simulated to evaluate the network requirement. The study case is London dense urban, southeast area, which tests whether it is possible to alleviate network congestion by making use of Wi-Fi in middle traffic indoor areas while allowing for outdoor area. Figure 20 shows the modelling in the simulation, and Table 21 shows the mobile and Wi-Fi demand parameters.

This use case is characterised by covering approximately 5.3 km^2 of flat terrain with green spaces. Most buildings are under 28 m tall, with around 70% not exceeding 20 m, although there are some exceptions exceeding 100 m in height. Regarding the traffic, small office and residential users use the mobile and Wi-Fi services for work, study, and family entertainment.



(a) Dense urban C



(b) 3D view in simulation

Figure 20: dense urban case

Table 21: mobile and Wi-Fi demand parameters

Parameter	Mobile	Wi-Fi
Population (P) (Total Working Day Population)	51,073	51,073
Area (A) (Central London: South East)	5.3 km2	5.3 km2
Population Density (PD)	9,636 People/km2	9,636 People/km2
Activity Factor (AF)	20%	20%
Total Offload Factor (OF) (= High Band + Indoor Mid Band)	35% (=25% + 10%)	-
Peak Active Users (U) (= P * AF * (1 – OF))	**6,639 Users**	-
Peak Active Outdoor Users (= 0.7 * U)	**4,648 Outdoor Users**	-
Peak Active Indoor Users (= 0.3 * U)	**1,991 Indoor Users**	**9,607 Users (100% Indoor)**

Peak Active User Density (UD) (= PD * AF * (1 – OF))	**1,253 Users/km2**	**1,813 Users/km2**
User Experienced DL Rate	50 Mbps	2,000 Mbps
User Experienced UL Rate	25 Mbps	1,000 Mbps

Table 22 presents the main network parameters used in this study. Parameters for both the existing 5G and the Upper 6 GHz band are provided for mobile, and existing 5 GHz and upper 6 GHz for Wi-Fi, as the 5G mobile and 5 GHz Wi-Fi results are given for reference.

Table 22: network parameters

Parameters	Configuration	
Wireless System	5G NR	Wi-Fi
Carrier Frequency	n78 3.5 GHz/Upper 6 GHz	Wi-Fi 5 GHz/Upper 6 GHz
Channel Bandwidth	80 MHz/200MHz	160MHz
Cell Tx Power per Port	46dBm	23dBm
Antenna Gain	15.88dBi/50-degree beam width	3dBi/Omni-directional
Duplex	TDD (DL: 60%)	TDD
MIMO	8x8	8x8
Cell EIRP	70.88 dBm	35 dBm

4.2.3.1 Coverage performance

Figure 21 presents the coverage performance. From the figure, the 99.26% area is covered if the compliance is -125dBm@SS RSRP for 5G NR, which means the network design meets the coverage requirements.

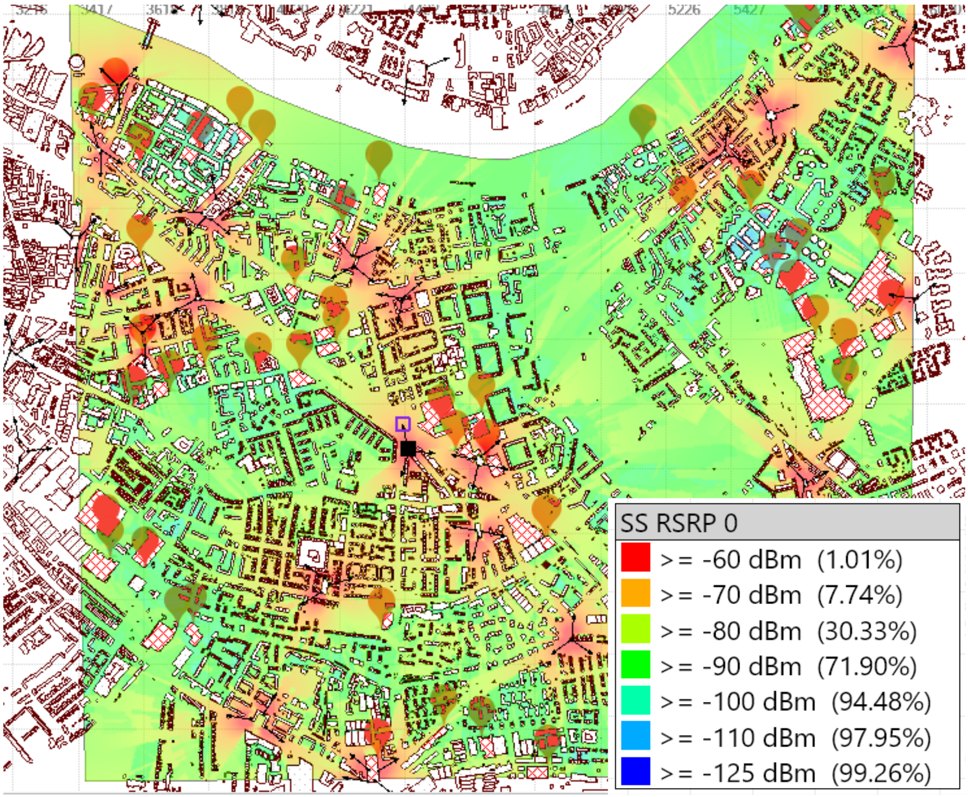


Figure 21: coverage performance

4.2.3.2 Performances of all Scenarios

Based on the simulation, the number of mobile base stations or Wi-Fi APs can be summarized, as shown in Table 23. From this table, Scenario 0 to 4 are defined in Table 7, when fixed the data rate for the future rate requirement, for example in 2035, and based on the estimation of CAPEX and OPEX in Section 4.2.1.2, spectrum sharing solution, i.e. Scenario 4, will reduce network deployment costs to achieve desired coverage and capacity because only 92 base stations and 1296 Wi-Fi APs are deployed, the cost is lower than the cost of 275 base stations and 2670 Wi-Fi APs in Scenario 1, or the cost of 239 base stations/small cells and 2670 Wi-Fi APs in Scenario 2, or the cost of 275 base stations and 1296 Wi-Fi APs in Scenario 3. WP3 will present how cost savings, or burdens for upper 6 GHz with spectrum sensing sharing mechanism and provide the accurate cost analysis for dense urban case.

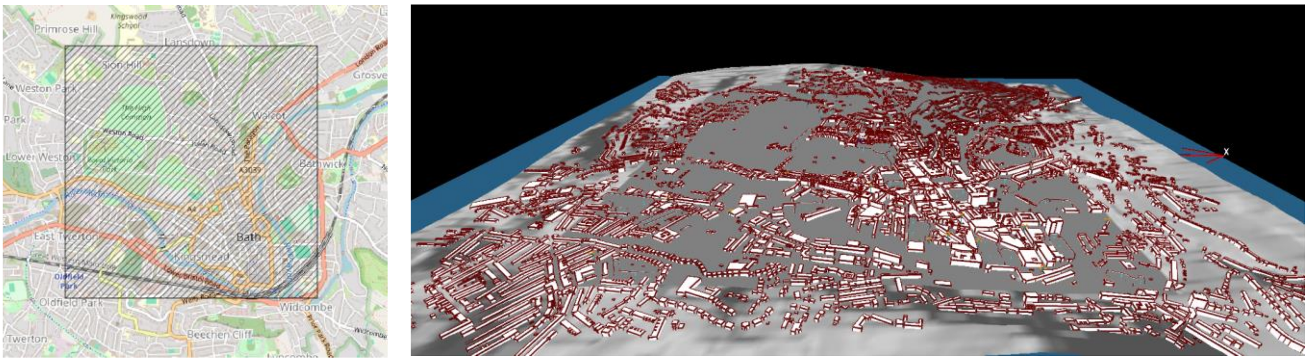
Table 23: summary of simulation

	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
No. of Mobile BSs	84	275	239	275	92
No. of Wi-Fi APs	391	2670	2670	1296	1296

4.2.4 Use case 4 – Urban case

The urban case would be simulated to evaluate the network requirement. The study case is Bath urban, which tests whether it is possible to alleviate network congestion by making use of Wi-Fi in high traffic indoor areas while allowing for outdoor area. Figure 22 shows the modelling in the simulation, and Table 24 shows the mobile and Wi-Fi demand parameters.

This use case is characterised by covering approximately 4 km^2 of limestone hills terrain with green spaces. Its topography, with steep hills and a compact urban core, alongside its traffic dynamics, provides a compelling lens for analysing mobile network performance.



(a) Urban case (b) 3D view in simulation

Figure 22: urban case

Table 24: mobile and Wi-Fi demand parameters

Parameter	Mobile	**Wi-Fi**
Population (P) (Total Residential Population)	21,210	21,210
Area (A) (Bath)	4 km2	4 km2
Population Density (PD)	5,303 People/km2	5,303 People/km2
Activity Factor (AF)	20%	20%
Total Offload Factor (OF) (= High Band + Indoor Mid Band)	30% (=20% + 10%)	-
Peak Active Users (U) (= P * AF * (1 – OF))	**2,969 Users**	-
Peak Active Outdoor Users (= 0.7 * U)	**2,079 Outdoor Users**	-
Peak Active Indoor Users (= 0.3 * U)	**890 Indoor Users**	**2,660 Users (100% Indoor)**

Peak Active User Density (UD) (= PD * AF * (1 – OF))	742 Users/km2	665 Users/km2
User Experienced DL Rate	50 Mbps	1,000 Mbps
User Experienced UL Rate	25 Mbps	500 Mbps

Table 25 presents the main network parameters used in this study. Parameters for both the existing 5G and the Upper 6 GHz band are provided for mobile, and existing 5 GHz and upper 6 GHz for Wi-Fi, as the 5G mobile and 5 GHz Wi-Fi results are given for reference.

Table 25: network parameters

Parameters	Configuration	
Wireless System	5G NR	Wi-Fi
Carrier Frequency	n78 3.5 GHz/Upper 6 GHz	Wi-Fi 5 GHz/Upper 6 GHz
Channel Bandwidth	80 MHz/200MHz	160MHz
Cell Tx Power per Port	43dBm	23dBm
Antenna Gain	15.88dBi/50-degree beam width	3dBi/Omni-directional
Duplex	TDD (DL: 60%)	TDD
MIMO	8x8	8x8
Cell EIRP	67.88 dBm	35 dBm

4.2.4.1 Coverage performance

Figure 23 presents the coverage performance. From the figure, the 99.26% area is covered if the compliance is -125dBm@SS RSRP for 5G NR, which means the network design meets the coverage requirements.

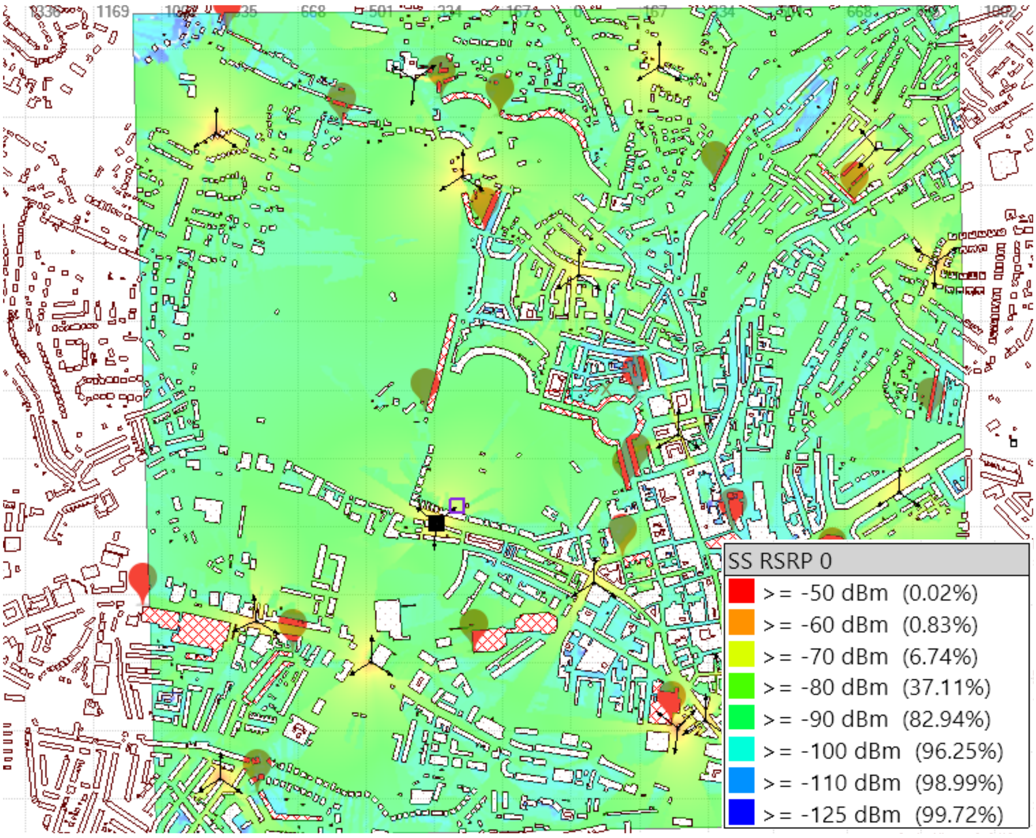


Figure 23: coverage performance

4.2.4.2 Performances of all Scenarios

Based on the simulation, the number of mobile base stations or Wi-Fi APs can be summarized, as shown in Table 26. From this table, Scenario 0 to 4 are defined in Table 7, when fixed the data rate for the future rate requirement, for example in 2035, and based on the estimation of CAPEX and OPEX in Section 4.2.1.2, spectrum sharing solution, i.e. Scenario 4, will reduce network deployment costs to achieve desired coverage and capacity because only 42 base stations and 596 Wi-Fi APs are deployed, the cost is lower than the cost of 109 base stations and 987 Wi-Fi APs in Scenario 1, or the cost of 96 base stations/small cells and 987 Wi-Fi APs in Scenario 2, or the cost of 109 base stations and 579 Wi-Fi APs in Scenario 3. WP3 will present how cost savings, or burdens for upper 6 GHz with spectrum sensing sharing mechanism and provide the accurate cost analysis for urban case.

Table 26: summary of simulation

	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
No. of Mobile BSs	45	109	96	109	42
No. of Wi-Fi APs	147	987	987	579	596

4.2.5 Use case 5 – Rural case

The rural case would be simulated to evaluate the network requirement. The study case is Northumberland, because lack of profitability in the current setup means that there are total and partial connectivity not-spots for mobile users. We are interested in how permissive licensing of the n77 spectrum band can be used to fill in these gaps for mobile users in rural areas such as Northumberland. Figure 24 shows the modelling in the simulation, and the users are distributed in the two villages and focus deployment on those (highlighted in red below), and Table 27 shows the mobile demand parameters.

(a) Rural case (b) Outdoor layout in simulation

Figure 24: rural case

Table 27: mobile demand parameters

Parameter	Mobile
Population (P) (Total Residential Population)	1,007
Area (A) (Northumberland)	25 km2
Population Density (PD)	40 People/km2
Activity Factor (AF)	20%
Total Offload Factor (OF) (= Indoor Mid Band)	10%
Average Active Users (U) (= P * AF * (1 – OF))	**181 Users**
Average Active User Density (UD) (= PD * AF * (1 – OF))	**7 Users/km2**
User Experienced DL Rate	10 Mbps
User Experienced UL Rate	1 Mbps

But in the case, only three scenarios are simulated, as shown in Table 28.

Table 28 simulation scenarios for rural case

Parameter	Simulate Existing Network	New Supply Scenarios to deliver target parameters	
	Existing Provision (Scenario 0)	Additional provision by MNOs (n78 band) (Scenario 1)	Mobile Sharing in n77 band (Scenario 2)
Spectrum Allocation (Mobile)	Current Frequency Provision (i.e., n78 Band for 5G)	Current Frequency Provision (i.e., n78 Band for 5G)	Current Frequency Provision (i.e., n78 Band for 5G) AND Permissive Licensing in n77 Band

Table 29 presents the main network parameters used in this study. Parameters for both the existing 5G and the Upper 6 GHz band are provided for mobile, and existing 5 GHz and upper 6 GHz for Wi-Fi, as the 5G mobile and 5 GHz Wi-Fi results are given for reference.

Table 29: network parameters

Parameters	Configuration	
Wireless System	5G NR	5G NR small cell
Carrier Frequency	n78 3.5 GHz	N77 3.7GHz
Channel Bandwidth	40 MHz	80MHz
Cell Tx Power per Port	43dBm	23dBm
Antenna Gain	15.88dBi/50-degree beam width	3dBi/Omni-directional
Duplex	TDD (DL: 60%)	TDD
MIMO	4x4	4x4
Cell EIRP	**64.88 dBm**	**32 dBm**

4.2.5.1 Coverage performance

Figure 25 presents the coverage performance. From the figure, the 100% area is covered if the compliance is -125dBm@SS RSRP for 5G NR, which means the network design meets the coverage requirements.

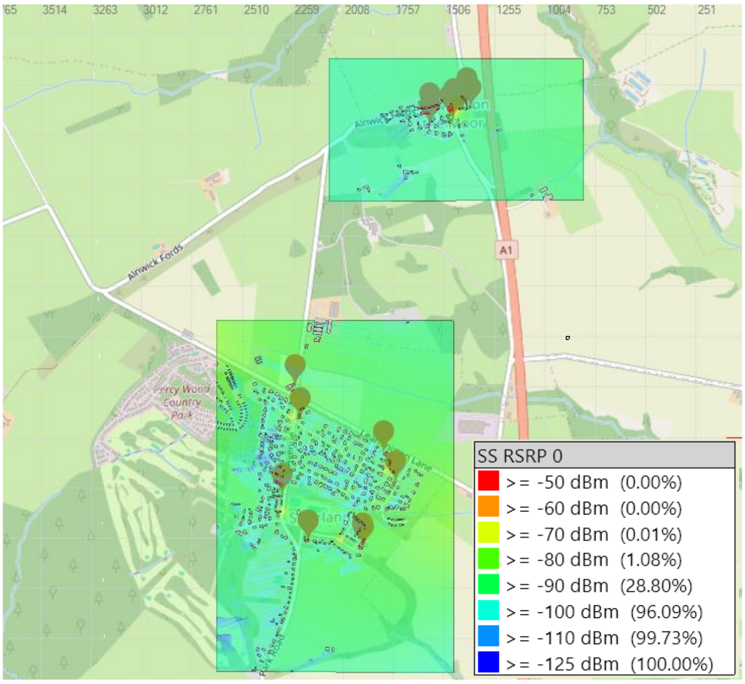


Figure 25: coverage performance

4.2.5.2 Performances of all Scenarios

Based on the simulation, the number of mobile base stations or Wi-Fi APs can be summarized, as shown in Table 30. From this table, Scenario 0 to 2 are defined in Table 28, when fixed the data rate for the future rate requirement, for example in 2035, and based on the estimation of CAPEX and OPEX in Section 4.2.1.2, spectrum sharing solution, i.e. Scenario 2, will reduce network deployment costs to achieve desired coverage and capacity because only 3 base stations and 8 small cells are deployed, the cost is lower than the cost of 9 base stations in Scenario 1. WP3 will present how cost savings, or burdens for upper 6 GHz with spectrum sensing sharing mechanism and provide the accurate cost analysis for urban case.

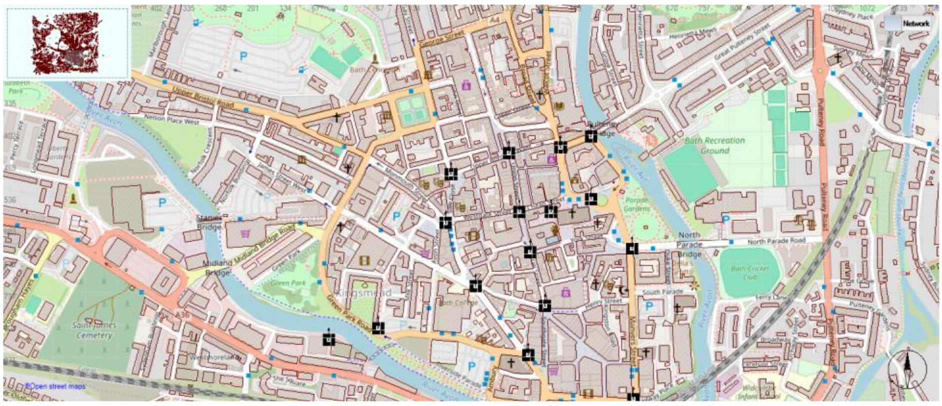
Table 30: summary of simulation

	Scenario 0	Scenario 1	Scenario 2
No. of Mobile BSs	3	9	3
No. of Small cells	-	-	8

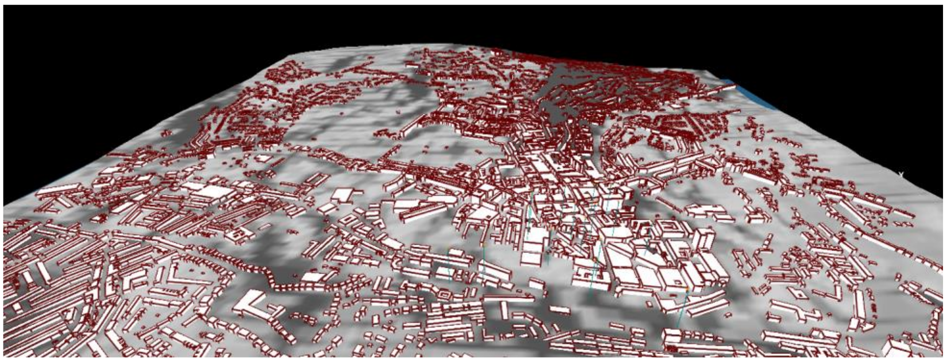
4.3 Simulation performance of IOPN

An independently operated private networks (IOPN) for spectrum sharing is a dedicated communication infrastructure (e.g., 5G,) that operates in a shared or licensed spectrum band. It enables authorized users (e.g., enterprises, government agencies, or industrial facilities) to access wireless resources while coexisting between private networks.

The case study of IOPN is in Bath for deploying and verifying the spectrum sharing solution, as show in Figure 26, where 16 Pico cells are deployed in the urban area, and the omnidirectional antennas are mounted on street lampposts with 4-meter heights.



(a) Network deployment



(b) 3D view

Figure 26: scenario for urban environment

The network parameters are shown in Table 31.

Table 31: network parameters

Parameters	Configuration
Wireless System	5G NR
Carrier Frequency	3.7 GHz Band n77
Channel Bandwidth	100 MHz
Cell Tx Power per Port	17 dBm (Pico Cells)
Antenna Gain	6 dBi Omni-directional
Duplex	TDD (DL: 80%)
MIMO	4x4

Cell EIRP	29 dBm

Figure 27 shows the coverage performance. From this result, the street area can be covered by the 16 Pico cells.

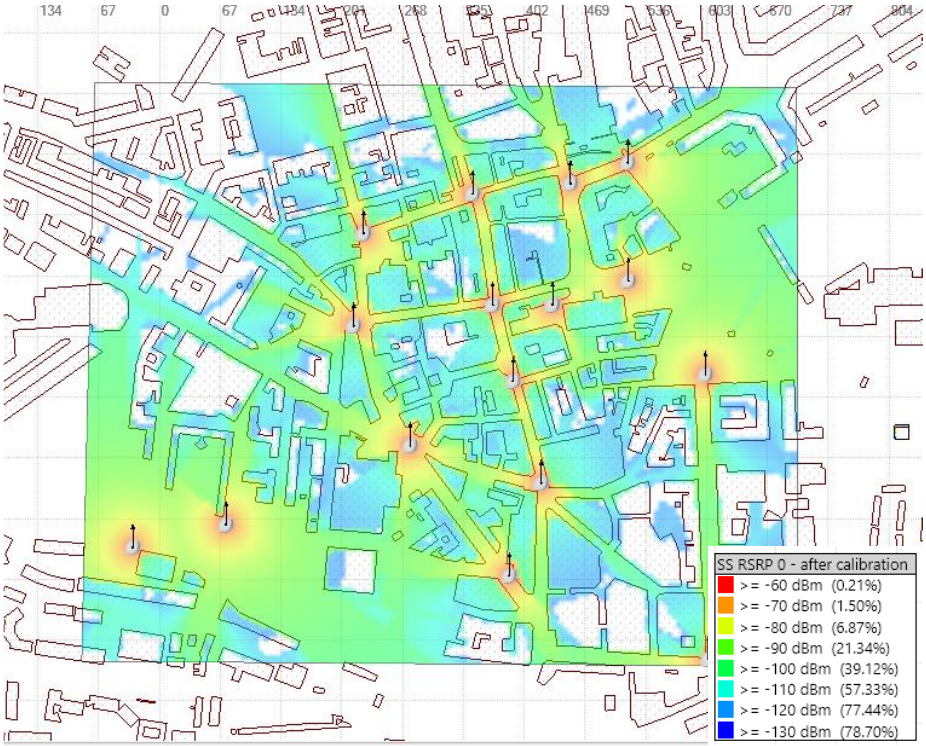


Figure 27: coverage performance

Table 32 measurement results

LAC	Level	LAT	LON	Z	PSC
81	-85	51.277	-2.5795	1	21
81	-90	51.277	-2.5798	1	21
81	-86	51.2771	-2.58	1	21
81	-80	51.2769	-2.5799	1	21
81	-81	51.2769	-2.5796	1	21
81	-73	51.2768	-2.5794	1	21
81	-83	51.2766	-2.5793	1	21
81	-72	51.2767	-2.5795	1	21
81	-80	51.2768	-2.5798	1	21
81	-83	51.2768	-2.5801	1	21
81	-85	51.2767	-2.5799	1	21
81	-78	51.2766	-2.5797	1	21
81	-84	51.2765	-2.5794	1	21
81	-91	51.2765	-2.5797	1	21
81	-93	51.2766	-2.5799	1	21
81	-92	51.2766	-2.5802	1	21
81	-88	51.2768	-2.5801	1	21
81	-79	51.2769	-2.5799	1	21
81	-82	51.2768	-2.5796	1	21
81	-76	51.2768	-2.5793	1	21

Based on the measurement results, as shown in Table 32, the PSC, i.e. Permanent Subscriber Identity Code, can be used to identify the different private networks. So, the total private network is shown in Figure 28.

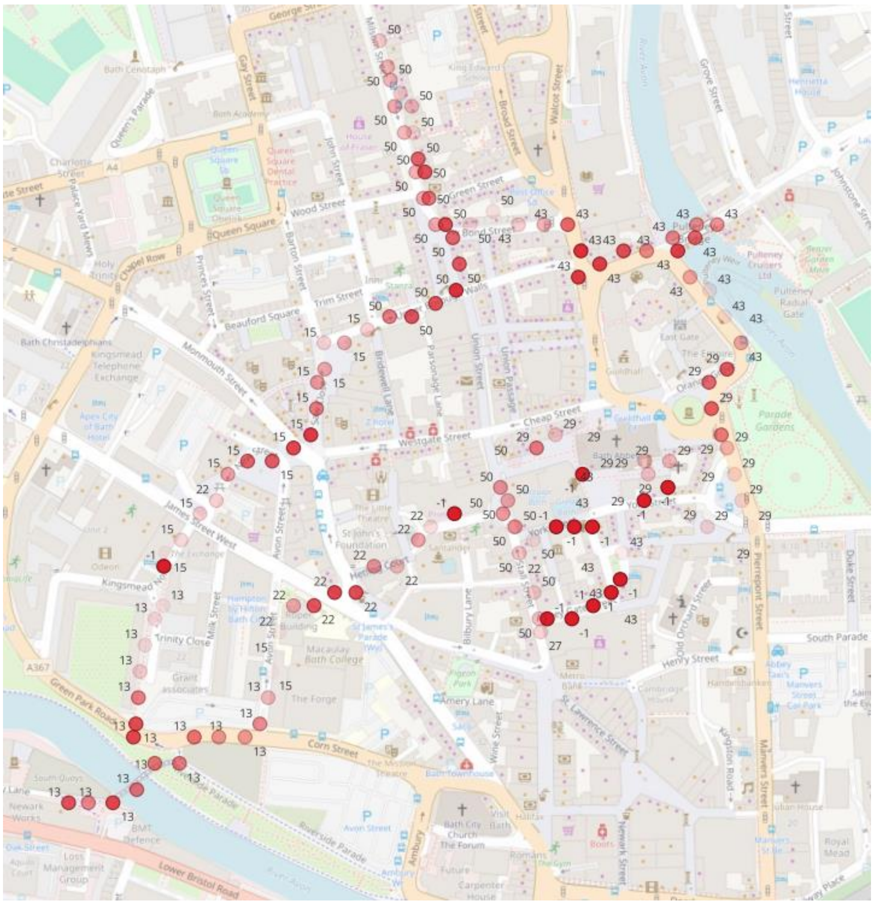
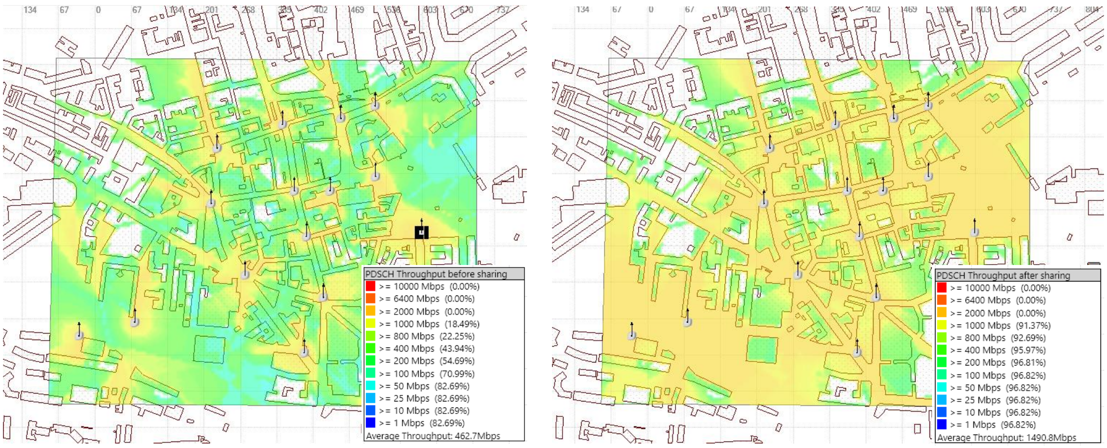


Figure 28: the private network

Figure 29 compares the throughput performance with/without spectrum sharing. Without spectrum sharing, these Pico cells will be deployed with band n77 and 100MHz bandwidth, and interference between different cells can impact the performance significantly. With spectrum sharing, -125dBm sensing threshold is set to hop the different channel, where total 3 channels are used for spectrum sharing, the interference can be reduced. Comparing the performance, the throughput is improved greatly. By comparing the spectral efficiency, as shown in Table 33, the spectral efficiency is improved about 7.39%, which means that spectrum sensing solution improves network performance and increases efficiency in the use of spectrum.



(a) Throughput before sharing

(b) Throughput after sharing

Figure 29: performance of spectrum sharing

Table 33: spectral efficiency comparison

	Before sharing (bps/Hz)	After sharing (bps/Hz)
Spectral efficiency	4.627	4.969

5. Conclusions

Spectrum sharing solutions can improves network performance, increases efficiency in the use of spectrum, and reduce network deployment costs to achieve desired coverage and capacity. In this deliverable, we have simulated the performance of spectrum sharing, and evaluated how cost savings, or how performance improving for mobile and Wi-Fi pair and IOPN pairs and output the comparison of CAPEX and OPEX for different scenarios, such as high-density urban, dense urban, urban, rural, and stadium, when fixing the technology and throughput target for economic analysis.

In order to simulate and analyse the spectrum sharing solution, this deliverable presents the ray-tracing propagation model calibration based on the measurement results from WP1 for accurate simulation.

The next steps for WP2 are as follows.

- Simulate the other pairs, i.e. mobile and fixed link, mobile and UWB, and mobile and scientific stations
- Simulate the more use cases, such as highway, so as to provide a comprehensive insight to scale the whole UK
- Further analyse the uplink impact on the spectrum sharing solution

References

[1] Ofcom, “Mobile and Wi-Fi in Upper 6 GHz – Why hybrid sharing matters,” May 2024

[2] WP3, “LE Inputs for Ranplan WP2 Simulations,” Version 5.2, February 2025