Deliverable D2.2: Simulation and modelling results and D2.3 data catalogue

Work Package 2 deliverable from spectrum sandbox project

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

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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 comprises three work packages:

1. Work package 1 (WP1) – Field trials in a sandbox environment to assess the feasibility of intensive spectrum sharing between different technology pairs.
2. 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.
3. 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 provides 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 comprises of Deliverable D2.2: Simulation and modelling results and D2.3 data catalogue. Deliverable D2.2 includes all the simulation and modelling results, outcomes of the work and the associated findings regarding the potential for more intensive spectrum sharing for the systems considered and under different input parameters. Deliverable D2.3 includes a data catalogue, listing all input data and parameters with associated sources and rationale.

All deliverables from WP2 and their due dates are listed in **Table 1-1**.

Table 1-1.: Summary of WP1 deliverables

Deliverable	Description	Due by
D2.1	D2.1 Simulation and modelling plan setting out the details of the systems and parameters to be evaluated and the modelling assumptions, in both technical and cost terms and how these will be validated using the measurements from WP1.	Issued
I2.2 Interim report	WP2 Report: Simulation and modelling results, providing the outcomes of the work and the associated findings for the potential for more intensive sharing for the systems considered and under different input parameters.	Issued
D2.2	**Final WP2 Report: Simulation and modelling results**	**This report**
D2.3	**Data catalogue, listing all input data and parameters with associated sources and rationale**	**This report**

1.1 Objective of the document

The primary objective of WP2 is to assess sharing solutions for a wider range of conditions, such as technical parameters, locations, frequencies, and technologies, using and expanding upon the insights gained from WP1.

WP2 evaluates whether the solutions and technical conditions tested in WP1 can offer improved spectrum sharing compared to current technical parameters, authorization methodologies, and real-world deployments. It also provides insights into potential trade-offs between coverage, capacity and Quality of

Experience (QoE) of networks and services and the basis upon which a number of systems could share the same spectrum.

1.2 Organisation of the document

In Section 2 we provide a comparison analysis of the propagation modelling used by Ofcom, when calculating the sterilisation areas, i.e.an area in which a piece of radio equipment risks causing harmful interference to (or receiving harmful interference from) another user [1] against other model predictions used by the industry. These are further compared with measurements to assess their pragmatic accuracy and to evaluate which method provides better results. A more accurate model, when employed in the spectrum assessment phase, leads to a higher degree of spectrum sharing intensity. We use the calibrated generalised model in our simulations to further assess the impact of our proposed solution to more location environments (urban, suburban, rural), frequencies and technology pairs.

In the same section, we also assess realistic Signal-to-Interference and Noise Ratio (SINR) requirements at the user equipment in order for a service to maintain its target performance. This part of the experiment involves the purposefully conducted experiment at Parsons Green, where we perform measurements in the presence of interfering signals and assessing the achieved throughput at the user equipment. The outcome of this analysis showcases that the acceptable interference targets could be relaxed, without any impact on the service performance at an existing location, thus improving the spectrum sharing.

In the following sections we present the information for each technology pair, which includes the parameters and assumptions, simulation and modelling results and model extensions to consider the impact of the different configuration parameters.

In Section 3, we discuss the Wi-Fi and mobile coexistence in the upper 6 GHz band.

In Section 4 we present the results for the independently operated private networks in the upper n77 band (3.8 – 4.2 GHz). The Shared Access Licence (SAL) framework in the UK provides a mechanism for accessing this spectrum for private networks and is the most important source of private network spectrum in the UK. According to the Ofcom consultation [2] published on November 23, many stakeholders expected demand for SAL to grow within the UK and several other countries to adopt similar approaches. There is significant interest in the industry in using private networks in the n77 band.

In sections 5 we provide a high-level assessment related to the other technology pairs that were not present in the WP1 field trials. These include fixed links, direct-to-device satellites in mobile bands and airborne base stations in mobile bands.

In the last section, Section 6, we summarise our findings and offer recommendations on how these can be applied in a real system, improving the spectrum sharing intensity.

2. Propagation loss predictions, calibration and comparisons

2.1 Propagation loss

As an initial step in our analysis, we assessed the coverage predictions generated by the procedure employed by Ofcom in the form of propagation loss predictions and compared them with other methods based on a ray-trace algorithm, a generalised model, as well as actual measurements.

2.1.1 Measurements

We performed measurements in two areas – St. Paul's Cathedral and Parson's Green. More information and outcomes of this work is included in the D1.5 deliverable [3].

The measurements at St. Paul's Cathedral were Continuous Wave (CW) measurements from three locations along Queen Victoria Street (QVS) for assessing the propagation loss in an urban environment (Table 2-1). The transmitter antennas were at a height of 6.75 m, while the height of the receiver locations was 2 m.

Every location in QVS transmits signals from two antennas, separated by few centimetres.

Table 2-1: Parameters for the QVS sites. All antennas have a height of 6.75m. Also shown in bold are the 6 sites selected for CW surveys.

QVS Site ID	CoL ID	Grid Reference	Antenna Type	Antenna Gain (dBi)
Loc2	8983	TQ 32544 81071	AW3870 Omni	8
Loc9	3998	TQ 31973 80934	AW3870 Omni	8
Loc10	8659	TQ 31815 80947	AW3870 Omni	7.8

The measurements at Parson's Green involved a micro- and a macrocell, along with 12 User Equipment (UEs), and they were used to gather connection information data, such as signal quality in the form of SINR, modulation and coding scheme (MCS) and MIMO rank, among others. These were processed and used to develop a model that estimates the achieved spectral efficiency based on the UE's received SINR.

2.1.2 Propagation model used by Ofcom

Ofcom calculates the prediction loss based on the International Telecommunication Union ITU-R P.452 pathloss model [4], which is a semi-deterministic model. That is, it considers underlying clutter and building data with a coarse resolution to calculate the 2D height profile loss, without considering the contributions of the lateral propagation phenomena (reflections/diffractions from the vertical surfaces and edges).

We arranged a workshop with Ofcom at an early stage of the project to gain a better understanding of their methodology for their coordination process in the shared access 3800-4200 MHz band. In particular we discussed how Ofcom predicts the extent of the "sterilised area" around a proposed site. Ofcom previously used ITU-R P.452 version 10 of [4] but has recently upgraded to version 18. Nevertheless, Ofcom uses clutter data at 50 m resolution to predict Received Signal Strength Indicator (RSSI) for coordination.

We requested that Ofcom use ITU-R P.452v18 to provide predictions in a grid format as follows:

- Pathloss values for the 3 locations along QVS – Loc2, Loc9 and Loc10 (site details as per Table 2-1)
- RSSI values, assuming omni antennas transmitting at the Medium Power (MP) SAL limit (42 dBm/20 MHz) and 3850 MHz with a 0 dBi receive antenna (which we refer to as the Ofcom Scenario)

Ofcom provided predictions for all 3 sites on 4th November:

- Using their latest model based on ITU-R P.452-18
- Providing RSSI (dBm) and path loss (dB) grids
- 1565 cols (X) by 1644 rows (Y) and 50 m cell size covering an area 78 km wide by 82 km high, extending beyond the M25 (which we refer to as the Ofcom Grid)

2.1.3 Generalised model (3GPP TR 38.901)

Generalised models, on the other hand, compute the propagation loss based on models derived from recorded data from many different measurement campaigns using a handful of parameters, such as frequency, distance, environment type, transmitter and receiver heights. In this analysis, we use the 3rd Generation Partnership Project (3GPP) TR 38.901 model [5], which is an industry standard for these types of analysis.

The specification estimates the pathloss for different environment types (UMi – urban microcell/street canyon scenario, UMa – urban rooftop deployment, and RMa – rural macrocell). For each case, the specification defines a set of equations to calculate the line-of-sight (LoS) and non-line-of-sight (NLoS) pathloss values, along with the probability of the user being in a LoS state.

For the comparison analysis with the measurements, we have used the UMi model, as it more appropriately describes the environmental conditions and transmitter configuration of the experiment.

2.1.4 Ray trace model

Finally, ray trace models use the digital twin of the environment to assess the wave propagation phenomena. The digital representation is based on detailed topographical data – such as terrain, clutter and buildings – with a resolution of 1 m or less. They provide a deterministic calculation of the prediction loss by identifying the possible rays from the transmitter to the receiver. Nonetheless, due to the variability of the building material and the non-specular surface of the obstacles, they suffer from a prediction error, albeit a smaller one, as we show in this comparison.

In our assessment, we use the ray trace model provided by Keima. Keima's model, Overture [6], considers reflections and refractions (transmissions) through buildings, where each building in the environment is associated with specific electromagnetic and refraction loss properties. Furthermore, the model provides the flexibility to adapt these properties during the calibration phase, to reduce the prediction loss when compared to actual field measurements.

2.2 Model comparisons

For this experiment, we measured the received signal from three transmitters that were located on Queen Victoria Street, at St. Paul's Cathedral. We then configured the propagation models we mentioned in the previous section, and we calculated the predicted received signal strength. The final part of this exercise was to compare the outcomes of the prediction methods with the measurements to make an assessment of the prediction accuracy of these models. The comparison data that we used are:

4. The current methodology that Ofcom uses (ITU-R P.452-18),
5. A generalised propagation model (3GPP TR 38.901),
6. The pre-calibrated 3D ray trace model,
7. The calibrated 3D ray trace model, and
8. Field measurements.

For the Ofcom and the generalised model comparisons, we used the pathloss predictions, along with the information about the transmit power, and the antenna orientation and radiation pattern to calculate the antenna gain from the transmitter to the receiver location. The received signal strength in this case is calculated as

$$\text{RSSI}_{\text{predicted}} = \text{P}_{\text{transmitter}} + \text{G}_{\text{transmitter}}(\theta) + \text{G}_{\text{receiver}} + \text{L}_{\text{pathloss}} \quad (1)$$

where θ is the azimuth of the receiver location with respect to the transmitter antenna's boresight, the transmitter antenna gain towards the receiver is $G_{transmitter}(\theta)$ and the receiver antenna gain, $G_{receiver}$, is -2 dB.

The generalised model requires further information on the LoS/NLoS state of the receivers with respect to the transmitter. This was not evident from the measurement records, and we used the modelling capabilities and high accuracy of the ray trace model to determine it.

The ray trace model inherently calculates the specific antenna gain for each outgoing ray, which is not always towards the exact direction to the receiver, but rather at a diverse angle of departure (for example, towards a wall, from which the signal bounces off to the receiver).

We display the transmitter related parameters in the following table:

Table 2-2. Configuration parameters for the base stations in Queen Victoria Street.

QVS ID	Latitude	Longitude	Antenna Gain [dBi]	Port 5 ETN [degrees]	Port 7 ETN [degrees]	Tx port power [dBm]
Loc2	51.51302	-0.09132	8	70	115	29
Loc9	51.51193	-0.0996	8	275	320	29.6
Loc1	51.51208	-0.10186	7.8	95	140	28.4

The noise floor for the receiver is between -120 and -110 dBm, so we excluded any measurement records below -110 dBm from the analysis.

In Figure 2-1, we plot the measured and predicted RSSI values with respect to distance. As a first note, there are some erroneous predictions for very short distances for the Ofcom-based predictions. This may be due to the limitation of the model that Ofcom utilises (known not to be valid for very short distances). Also, the same model seems to consider erroneously some receiver points in LoS state, and this may be due to the low resolution of the topographical data used. For the NLoS locations, Ofcom underestimates the received signal strength, or equally stated, overestimates the pathloss.

On the other hand, the generalised model exhibits a lower spread, which can be explained by the simplicity of the model itself (mainly distance and frequency). That spread is due to the differences of the transmitter antenna gain towards each receiver location (otherwise, for a perfect omnidirectional antenna, you could expect two perfect lines, one for LoS and one for NLoS). The generalised model also seems to overestimate the received signal for some LoS points, but this may be due to the fact that these points, even though they were categorised as LoS, in reality they were not (due to street clutter or other obstacles along the path).

The predictions from Overture follow more closely the actual measurement records. The received signal is a summation of (many) multipaths, each with different power due the various effects of the environment and transmitter antenna gain value. The ITU and 3GPP model do not consider such information (the transmitter antenna gain in this case is the antenna gain towards the direction of the receiver point, irrespective if the dominant ray path follows that direction), while the ray trace model does, which contributes to its accuracy. During the calibration phase, the tool optimises the electromagnetic properties of the buildings to minimise the prediction error.

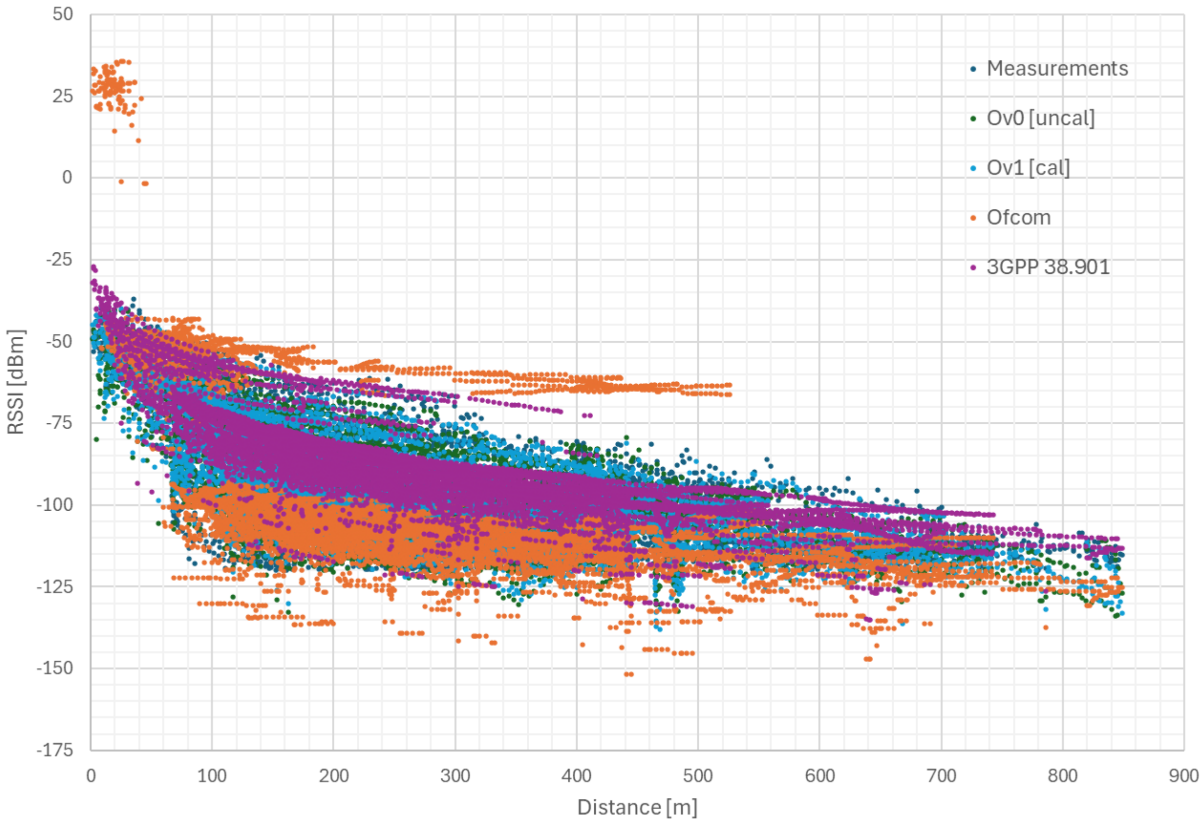


Figure 2-1. Plotting the received signal strength (RSSI) vs. distance for the measurement and predicted points.

Based on the measurements and the predictions from each model, we calculated the accuracy levels for each case, and we display this comparison exercise in Table 2-3.

The results show that the calibrated 3D ray-trace model achieved the best performance, with the second lowest mean error[1] and lowest standard deviation. The predictions based on the model that Ofcom uses had the worst performance, with the worst mean error and highest standard deviation. The 3GPP model was in between these two extremes.

Table 2-3. Accuracy of the prediction models.

	Mean [dB]	Standard deviation [dB]
3GPP LoS	5.03	12.48
3GPP NLoS	3.72	13.56
Ofcom	-8.26	21.70
Keima Overture (uncalibrated)	-1.04	7.79

[1] The calibrated model didn't achieve the lowest mean error because it was calibrated on the whole measurement set, rather than only for the points where measurement RSSI was greater than -110 dBm, while the statistics in the table consider only the latter values.

Keima Overture (calibrated)	-1.06	6.68

2.3 Generalised model extensions

Given the comparison results, we conclude that the generalised model provides good predictions (better than the model employed by Ofcom), and therefore, we will use this model as is when assessing the impact between the different technologies in different environments and configurations, where applicable. This model, 3GPP 38.901, will be used for the prediction loss for the terrestrial scenarios (for private and cellular networks, and between cellular network and fixed service).

For the Non-terrestrial network (NTN) related scenarios, where we need to predict the communication loss between the non-terrestrial platform and the terrestrial network, we use the 3GPP TR 38.811 model[7].

2.4 SINR to throughput mapping

In the next experiment, we use the measurement set from Parson's Green to map the achieved SINR levels to spectral efficiency. The measurements in Parson's Green include data from many UEs and therefore a better understanding of the service levels that the users experience.

At every measurement point, we get information about the SINR, the achieved layer 1 (L1) throughput, the average MIMO rank and the average MCS. From those, we compute the spectral efficiency (SE) in terms of bits/RE (resource element) and bits/s/Hz.

The measurement data show a relatively large spread between SINR and SE (Figure 2-2). In a general trend, as the SINR increases, so is the achieved SE. We have created a model (in a similar manner to [8][9]), that estimates the spectral efficiency considering the SINR, the environment type, and number of transmitter and receiver antennas (orange dots in Figure 2-2).

$$\mathrm{SE[bits/s/Hz]} = f(\mathrm{SINR}, \mathrm{N}_{Tx}, \mathrm{N}_{Rx}, \text{environment type}) \tag{2}$$

The model displays a very good agreement with the measurements, and it also allows us to extend it to different base station and UE configurations, and environments.

We use this model to calculate the achieved throughput levels for each active user in the (victim) network in the simulation based on the calculated SINR, and to quantify how an interfering (aggressor) network affects that and the overall network statistics of the victim network.

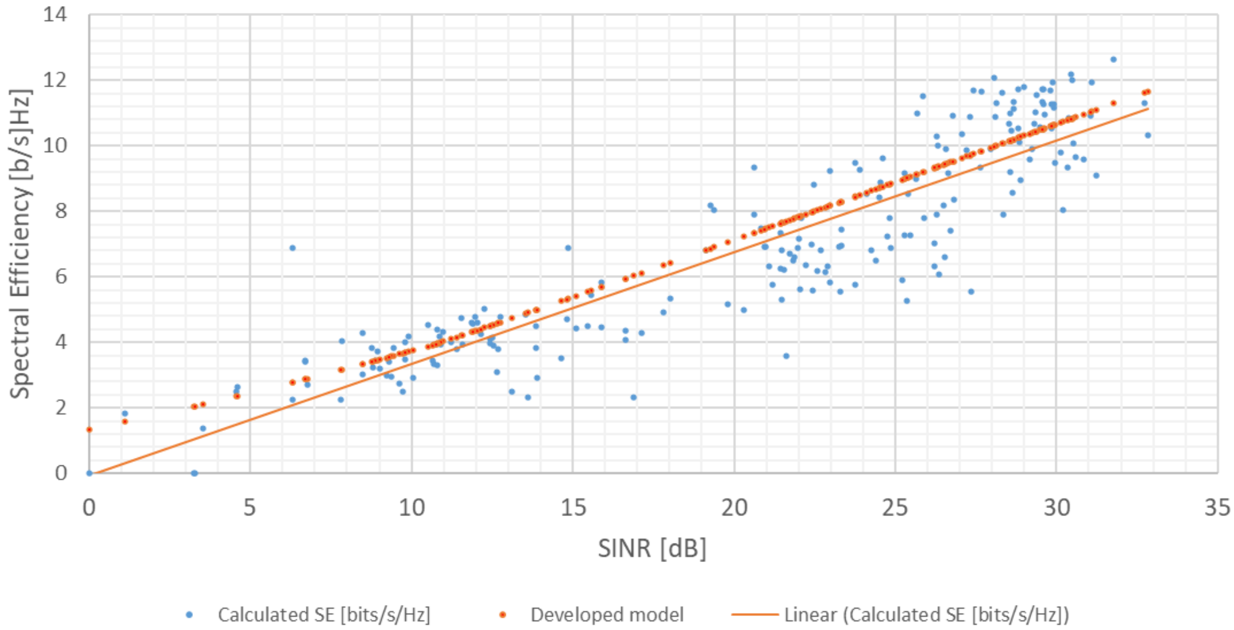


Figure 2-2. The measured and modelled SINR vs. spectral efficiency

2.5 The use of generalised channel models Concluding remarks

The analysis has shown that we can increase the accuracy of the prediction methodology if we employ a deterministic model (such as a ray trace algorithm). It is important though to note that we cannot generalise this statement, that is, that all deterministic models and in all environments are better than the current procedure that Ofcom uses, as the capabilities of these models differ and are dependent on the environment. The results show that, for this specific environment (St. Paul’s Cathedral, an urban environment) and the model we used (Keima’s Overture), we can achieve a superior performance in terms of mean prediction error and standard deviation.

It will be very beneficial to test this hypothesis in more locations, within the urban fabric, and more environment types, such as suburban and rural, or even including more prediction models in the analysis, to be able to make a more assertive comment. What this may also indicate is that the license process may need to include a multi-model approach, which is used to calculate the effects of the candidate network to better understand its possible effects on incumbent networks.

We have also successfully created a model to map SINR values to spectral efficiency. This model is based on measurements at Parson’s Green. The measurement apparatus included 12 collocated UEs in three selected locations with good, fair and bad propagation conditions.

We can improve the accuracy of this model by having the measuring locations distinct for each UE and by being able to measure in real time how the variety of the propagation conditions affect the UE service. We can also extend such measurements to include more cell locations in different environment types, to ensure that we have better representations of the realistic behaviour of the network.

3. Wi-Fi and mobile in the upper 6 GHz band

The upper 6 GHz band is currently a popular frequency band under consideration for mobile and Wi-Fi services around the world. At WRC-23, the frequency bands 6425-7125 MHz in Region 1 (and some parts in Region 2) were identified for International Mobile Telecommunications (IMT) and Wireless Access Systems/Radio Local Area Network (WAS/RLANs) such as Wi-Fi. The lengthy discussions at WRC show this band's strong global interest for mobile and Wi-Fi users. European Conference of Postal and Telecommunications Administrations (CEPT) is also conducting feasibility and sharing studies on the potential shared use of the upper 6GHz band between this system pair. There is also significant interest in this band from industry – as seen by the

Ofcom consultation in July 2023 [**10**]. Respondents, in general, agreed that hybrid mechanisms should be developed via industry collaboration and international harmonisation. In May 2024, Ofcom published its vision [**11**] for the Upper 6 GHz band in the UK, stating that Ofcom prefers sharing between mobile and Wi-Fi to unlock the maximum possible benefits of the band to all users. The CEPT has been actively assessing the future use of the upper 6 GHz band, specifically from 6425 to 7125 MHz. This assessment includes conducting coexistence studies to evaluate the feasibility of sharing this spectrum between Wireless Access Systems, such as Radio Local Area Networks (WAS/RLANs), and existing services. Additionally, CEPT has been working on developing harmonised technical conditions to support the potential introduction of these new services within the band.

On 13 February 2025, Ofcom published [**12**] a consultation proposing expanded access to the 6 GHz spectrum band for Wi-Fi and mobile services. For the Upper 6 GHz band (6425–7125 MHz), Ofcom proposes a phased approach: initially permitting low-power indoor Wi-Fi, with mobile services to be introduced subsequently, once European harmonisation is more mature. Ofcom is planning to introduce sharing mechanisms to facilitate coexistence between both services. Ofcom believes that this phased approach will maximise the benefits to citizens and consumers, allowing Wi-Fi to seed the market with devices capable of using Upper 6 GHz, and providing greater certainty to both services.

3.1 Introduction

In this section, we will evaluate the performance impact of spectrum sharing between mobile and Wi-Fi deployments operating in the same band. We will focus on the impact between macro mobile deployments and Indoor Wi-Fi deployments.

We will first establish a baseline by studying the independent operation of the two different technologies, Wi-Fi and mobile in upper 6 GHz, assuming no geographical overlap or cross-interference, and this will provide a reference to be used in the following comparisons.

As part of the baseline procedure, we will also evaluate the impact on performance (e.g. throughput, SINR level, etc.) of the uncoordinated usage of the same channel by the two technologies in the case of geographical overlap (i.e. uncontrolled cross technology interference).

Then, we will study the impact of co-channel coexistence using the cross-technology signalling sharing solution modelled in the figure below.

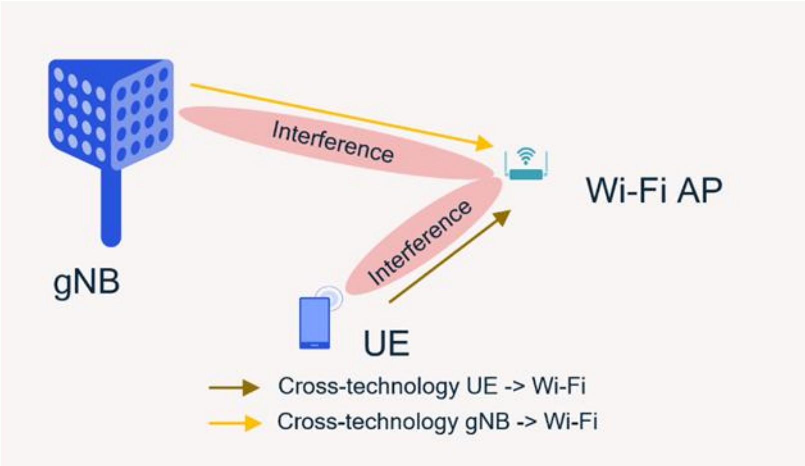


Figure 3-1. A graphical description of the system model for cross-technology signalling for Wi-Fi and mobile coexistence in Upper 6 GHz.

In detail, we use a simulator that will model the Coupling Loss between the mobile BS and/or active UEs and the active Wi-Fi Access Points (APs), also taking into consideration the impact of BS Active Antenna System (AAS) beamforming, building entry loss (for indoor Wi-Fi APs), pathloss, and other propagation phenomena, and will accordingly compute the expected level of cross technology signalling received by the AP.

It will be, therefore, possible to associate each active Wi-Fi AP deployed in the network region with a certain probability of successful access to the channel for each snapshot. The simulator then implements a straightforward detect and vacate policy, according to which the active Wi-Fi AP will vacate the channel if it has successfully been able to decode the cross-technology signalling message. The probability of successful access is expected to depend on the distance and channel conditions between the two deployments.

The simulator will then model the interference from the active Wi-Fi AP that has not vacated the channel as additional interference contribution, and produce metrics for the IMT throughput that show the impact of the SINR reduction, if any.

The observations derived from the simulation results in this evaluation can be compared with the results collected during the work from the field trials in WP1. In particular, the conclusions on both cross-signalling detection threshold and probabilities of successful reception, and on the impact of cross-technology interference to each deployment can be compared with the conclusions derived from measurement results coming out of WP1.

The results are expected to inform the predictions on the impact of cross-technology signalling on the different systems, and to show how the control parameters can be tuned to trade-off different choices on spectrum sharing actions.

The sharing technique has been studied for the upper 6 GHz band, but some of the principles can also be applied to other bands in which sharing spectrum between Wi-Fi and IMT is under consideration, or with other technologies if they accordingly implement the signalling.

3.2 Parameter definition and assumptions

For Wi-Fi and Mobile coexistence, reference cellular parameters will include CEPT PT1 assumptions (including but not limited to standard transmit power for macro IMT deployments). The maximum EIRP simulated will be 83 dBm. The minimum power that will be simulated is 58 dBm.

See [13], Section 3.2.1.4 and Table 3.1 for a list of typical IMT deployment parameters.

3.2.1 Wi-Fi system parameters

The Wi-Fi system values in the table below are extracted from the Liason Statement exchanged between CEPT PT1 and Project Team SE 45 on the topic of WAS/RLAN parameters for sharing and compatibility studies in the upper 6 GHz band. [14]. The list of parameters provided by Project Team SE45 includes Wi-Fi AP receiver and transmitter parameters (including antenna gain and transmit power), and deployment parameters, see Table 3-1. When SE45 RX Assumptions are used in the results, these parameters have been used to generate the corresponding curves

Table 3-1. Parameters and assumptions for the Wi-Fi system modelling

	Wi-Fi	
	AP	STA
Frequency band	6425-7125MHz	
Bandwidth	20 MHz receiver for Cross Technology Signalling 80 MHz transmitter for assessment of impact to IMT	
Transmit power	200mW (LPI) [13]	
Antenna gain (Normalised)	Table 2 (RX), 5 (TX) in [13]	Tables 3, 4 (RX) and 6, 7 (TX) in [13]
Antenna height	Electronic Communications Committee (ECC)13�]	
Noise figure	9 dB	
Propagation model	Free Space Path Loss Calculator (FSPL) for d13�]	
RF Activity Factor	2.45%	
Population, Market Adoption and Upper 6 GHz factor	Dense Urban: 20000 hab/kmsq Suburban: 2000 hab/kmsq	

For the decoding of a cross-technology signalling message, we have assumed an SINR threshold of **4dB**. This is based on an evaluation of the datasheets from Wi-Fi APs available on the market, and their sensitivity levels.

Based on the population and all factors related to market and penetration, including RF Activity Factor, we have concluded that 1 AP per IMT sector would be active per each snapshot.

3.2.2 Wi-Fi Access Point location

The simulation and modelling results in the next section shows the impact of Wi-Fi AP interference on IMT DL and UL throughput. As will be observed, the results are sensitive to the relative location of Wi-Fi APs concerning active UEs, so two options of relative location between the deployment have been studied.

For the “colocated AP” case, the Wi-Fi APs are always in proximity to the active IMT UEs (10m radius). Instead, in the case of “random AP” deployment, Wi-Fi APs are randomly located within the cell with identically distributed probability. APs are always located indoors.
The interest in the colocated case is motivated by the fact that if IMT and Wi-Fi are deployed in the same geographical area, the victim users (e.g. IMT UE or BS) will experience a very different impact depending on their relative location compared to the aggressor users (e.g. Wi-Fi APs). In this case, the average activity factor of WAS/RLANs is not sufficient to fully characterise the potential interference impact from Wi-Fi AP to IMT UEs.
Indeed, the average performance in time for colocated users can largely differ from the UE performance averaged across all locations. Hence, the interference from WAS/RLANs colocated to IMT UEs, assuming active WAS/RLAN transmissions, has been included in the study. This corresponds to a worst-case analysis as, in practice, WAS/RLANs do not transmit continuously, and IMT UEs do not receive continuously.

3.2.3 IMT system parameters

Table 3-2 shows the IMT parameters used for the simulation.

The following scenarios for IMT Deployments have been considered: Dense Urban and Suburban. Aligned with the ongoing priorities in the regulatory discussions (e.g. ITU Working Party 5D, CEPT PT1), rural deployment has been considered to have a lower priority, so it was not included in the study. However, there should be no obstacle to extend the conclusions to that scenario when applicable.

Table 3-2: IMT System Parameters used in the Coexistence Simulations

Parameter	Base Station (AAS)	Mobile Station (UE)
Carrier Frequency	6475 – 7075 MHz	
Duplex Method	TDD	
Channel bandwidth	100 MHz;	
Maximum / typical output power	See **Table 3-4**	23 dBm
Noise Figure	6 dB (Wide Area BS)	9 dB
Antenna Height	See **Table 3-3**	See **Table 3-4**

Table 3-3: IMT Deployment Parameters used in the Coexistence Simulations

IMT Deployment Parameter	Urban Macro
Deployment Layout	Hexagonal Cell, 19 Cells, 57 BSs (**Note 1**)
Inter-Site Distance (ISD)	450m for Dense Urban 900 m for Suburban

Sectorization	3 sectors per Cell
Frequency reuse	1
Time Division Duplex (TDD) / Frequency Division Duplex (FDD)	TDD
UE Indoor/Outdoor Probability	70/30%
Indoor user terminal penetration loss	Rec. ITU-R P.2109
Network Loading Factor	100%
Note 1: "1 BS" = 1 sector in 3-sector cell.	

Table 3-4: IMT Base Station Parameters used in the Coexistence Simulations

IMT Base Station Parameters	Urban Macro	Suburban
Antenna height	18 m	20 m
Antenna pattern	Refer to Recommendation ITU-R M.2101	
Element gain (dBi) **(Note 1)**	5.5	6.4
Horizontal/vertical 3 dB beamwidth of single element (degree)	90º for H 90º for V	90 for H 65 for V
Horizontal/vertical fronttoback ratio (dB)	30 for both H/V	
Antenna polarization	Linear ±45º	
Antenna array configuration (Row × Column) **(Note 2)**	16 × 8 elements	
Horizontal/Vertical radiating element spacing	0.5 of wavelength for H, 0.5 of wavelength for V	0.5 of wavelength for H, 0.7 of wavelength for V
Array Ohmic loss (dB) **(Note 1)**	2	
Conducted power (before Ohmic loss) per antenna element (dBm) **(Note 9)**	32 (for 83 dBm EIRP) 22 (for 73 dBm EIRP) 14 (for 65 dBm EIRP) 7 (for 58 dBm EIRP)	

Base station maximum coverage angle in the horizontal plane (degrees)	±60	
Base station vertical coverage range (degrees) **(Notes 3, 4, 10)**	90-120	
Mechanical downtilt (degrees) **(Note 4)**	10	6
Note 1: The element gain includes the array ohmic loss. This means that the parameter "array ohmic loss" is not needed for the calculation of the BS composite antenna gain and e.i.r.p. Note 2: Row × Column means there are Row vertical and Column horizontal radiating elements, Note 3: The vertical coverage range is given in global coordinate system, i.e. 90° being at the horizon. Note 4: The vertical coverage range includes the mechanical downtilt. Note 5: The conducted power per element assumes 8 × 8 × 2 and 32 x 16 x 2 elements, respectively, (i.e. power per H/V polarized element). Note 9: In sharing studies, the transmit power calculated using the conducted power (before Ohmic loss) per antenna element is applied to the bandwidth given in Table 1. Note 10: In sharing studies, the UEs that are below the coverage range can be considered to be served by the "lower" bound of the electrical beam, i.e. beam steered towards the max. coverage angle. A minimum BS-UE distance along the ground of 35 m should be used for urban macro.		

Table 3-5: IMT User Equipment Parameters used in the Coexistence Simulations

IMT User Equipment Parameters	Urban Macro
Antenna height	Outdoor UEs: 1.5m Indoor UEs: Random based on 3GPP TR 36.873
User equipment density for terminals that are transmitting simultaneously	1 UE per sector
Antenna gain for user terminals	−4 dBi
Body Loss	4 dB
Average user terminal output power	Use transmit power control
Power Control	Refer to Recommendation ITU-R M.2101 Annex 1, section 4.1

3.2.4 IMT Base Station cross technology signalling antenna beam choice

The results in the next section assume that the transmission of Cross Technology Signalling (XTS) is associated with the use of broadcast transmission beamforming, when the source of the XTS is the IMT Base Station.

While the use of data beamforming allows for a more directional transmission and higher spatial selectivity, due to the broadcast nature of the XTS transmission, broadcast beams (e.g. Synchronization Signal Block or SSB beams) seem to be better suited to achieve a larger coverage. The beam choice also has an impact on the design of the XTS scheduling, WLAN detection periodicity requirements, and time before accessing the channel.

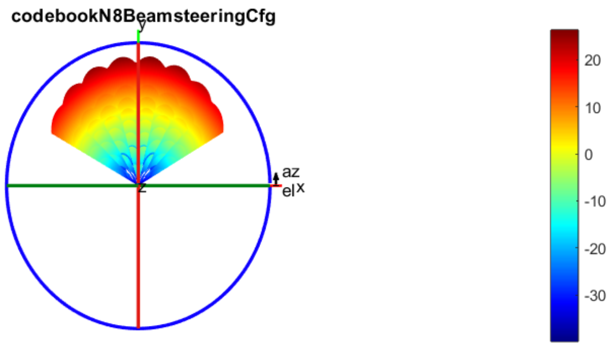
For the beamforming choice of broadcast transmission, we assume a number N=8 beams which are equally distributed in the sector's azimuth domain (120 degrees). Since the codebook design is typically implementation specific, the beams configuration adopted for the XTS transmission represents an assumption needed for the simulations, while further optimisation or differences cannot be excluded when evaluating more realistic implementations.

Figure 3-2: IMT BS Broadcast Codebook Beam Pattern (Composite)shows a graphical representation of the composite beam created by illuminating all the beams in the codebook used to generate results for broadcast beams in the report, unless otherwise mentioned.

The top picture in Figure 3-2 represents a top view of the composite beam shape limited to a single sector coverage of 120 degrees in the azimuth domain, while the bottom image shows the side view of the composite beam shape in the vertical domain.

Antenna array downtilting, included in the simulation results as per assumptions, is not represented here and it will result in the main lobe pointing downwards with respect to the horizon/y-axis.

The colour according to the correspondent colourbar represents the antenna gain (in dBi).



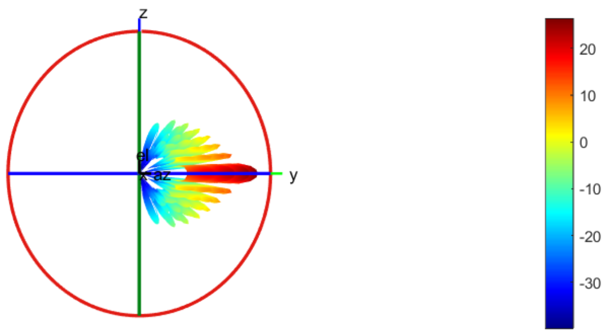


Figure 3-2: IMT BS Broadcast Codebook Beam Pattern (Composite)

3.3 Simulation and modelling results

3.3.1 Results Introduction

This section provides an explanation of how to read the results figures presented in the following sections.

The Y Axis represents the cumulative distribution function (CDF) , i.e. for a real-valued random variable X representing the metric of interest, the CDF is given by the following expression F(x) = Prob (X < x) [%].

To assess XTS Performances the following metrics are considered in the plots:

- XTS Signal Power [dBm]: Total Cross Technology Received Signal Strength.
- SINR [dB]: XTS Signal Power to Interference and Noise Ratio.
  SINR = [Signal / (Interférence + Noise)] (dB).
- XTS Signal Power [dBm], when SINR > SINR Threshold: Total Cross Technology Received Signal Strength, assuming BW = 20MHz, collected only when the SINR metric for the same observation is larger than the assumed threshold of [4] dB, according to the assumptions.

To assess the impact from sharing with XTS to IMT the following metrics are considered in the plots:

- DL and UL Throughput [Mbps], according to industry standard methodology (3GPP TR 38.803 - 5.2.7) based on SINR. The reduction of throughput presented with respect to the baseline (*IMT Only*) shows the impact of sharing.

To assess the impact from sharing with XTS to Wi-Fi, the percentage of active Wi-Fi for each scenario is included when throughput results with active sharing are presented.

3.3.2 Baseline results

To assess the impact from sharing with XTS to IMT we establish in this section two different reference performances, according to the following description:

- IMT Only throughput (DL and UL) assuming that there are no active Wi-Fi deployments in the area This will be included in the other result plots as a reference baseline level.
- IMT + Wi-Fi throughput (DL and UL) assuming both technologies operate in the same geographical location, without the use of any sharing techniques (i.e. uncontrolled deployment).

Throughput for UEs that do not achieve sufficient SINR is not shown in the plot.

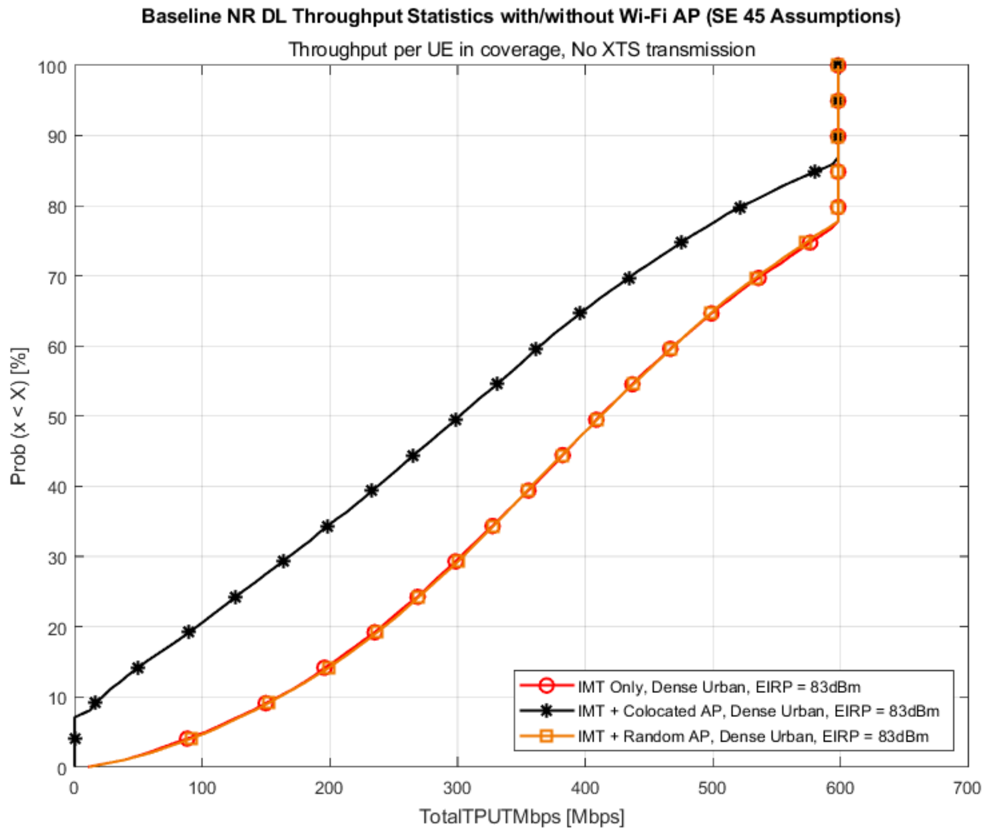


Figure 3-3: Reference IMT DL Throughput without sharing techniques

For the IMT + AP case, since the assumption is no sharing technique the results above assume that **100**% of the active Wi-Fi APs are using the channel (1 AP per sector according to the system parameters).

The figure above shows that:

- For the case of IMT + Random AP, there is little impact to DL performances. If the IMT UE and Wi-Fi AP are operating in uncorrelated locations the results show that the interference from other IMT BS is the dominating contribution.
- However, the results for IMT + Colocated AP show that there’s an average reduction of **27%** for the DL throughput when the IMT UE and Wi-Fi AP are operating in the same location.

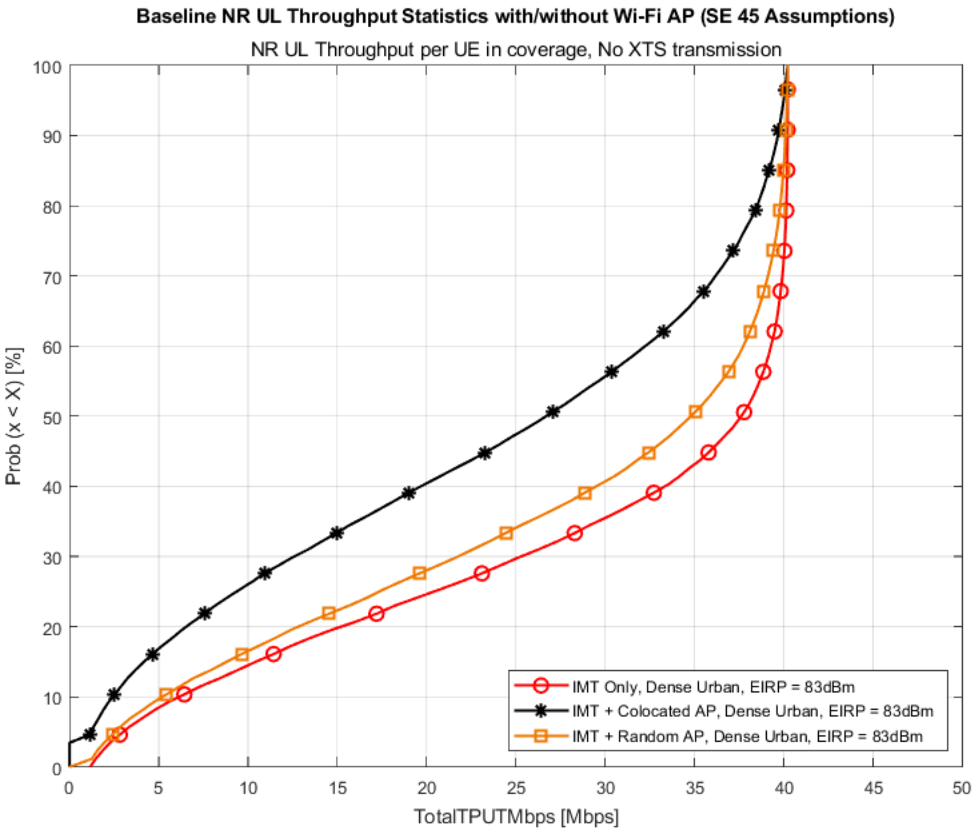


Figure 3-4: 3-5Reference IMT UL Throughput without sharing techniques

For the IMT + AP case, since it was assumed that no sharing technique was implemented in this scenario, 100% of the active Wi-Fi APs are using the channel (1 AP per sector according to the system parameters).

The figure above shows that:

- For the case of IMT + Random AP, the impact to UL performances is not negligible. Even if the IMT UE and Wi-Fi AP are operating in uncorrelated locations, the interference contribution from the Wi-Fi AP is received at the IMT BS, reducing the IMT UE SINR and impacting the UL throughput by up to **10%**.
- This impact is more pronounced if the Wi-Fi AP is colocated with the IMT UE, and the UL throughput is reduced by up to **34%** when the IMT UE and Wi-Fi AP are operating in the same location.

In the next section, we will present the impact of co-channel coexistence using the cross-technology signalling sharing solution.

3.3.3 XTS Performances: IMT Base Station as Source

This section presents two set of simulation results for the XTS reception statistics at the Wi-Fi AP, assuming IMT Base Station transmitting XTS using broadcast beams.

These results are included in the report as a necessary starting point to study the performance of cross-technology signalling as a viable method for spectrum sharing, considering first the likelihood of Wi-Fi to successfully identify the presence of the IMT deployment.

Since the sharing scheme studied here is based on decoding of an 802.11bc frame, we expect detection performances to be dependent on SINR of the received signal, and this is the distribution we have studied first.

After considering the detection performance, we look at the received signal strength statistics. This is motivated by the fact that Wi-Fi APs in the sharing simulation will vacate the channel when IMT XTS is received above a certain threshold, and the characterisation of XTS received power and SINR statistics provides a comprehensive picture. The following sections containing sharing results will study the impact of the vacation policy and threshold choice.

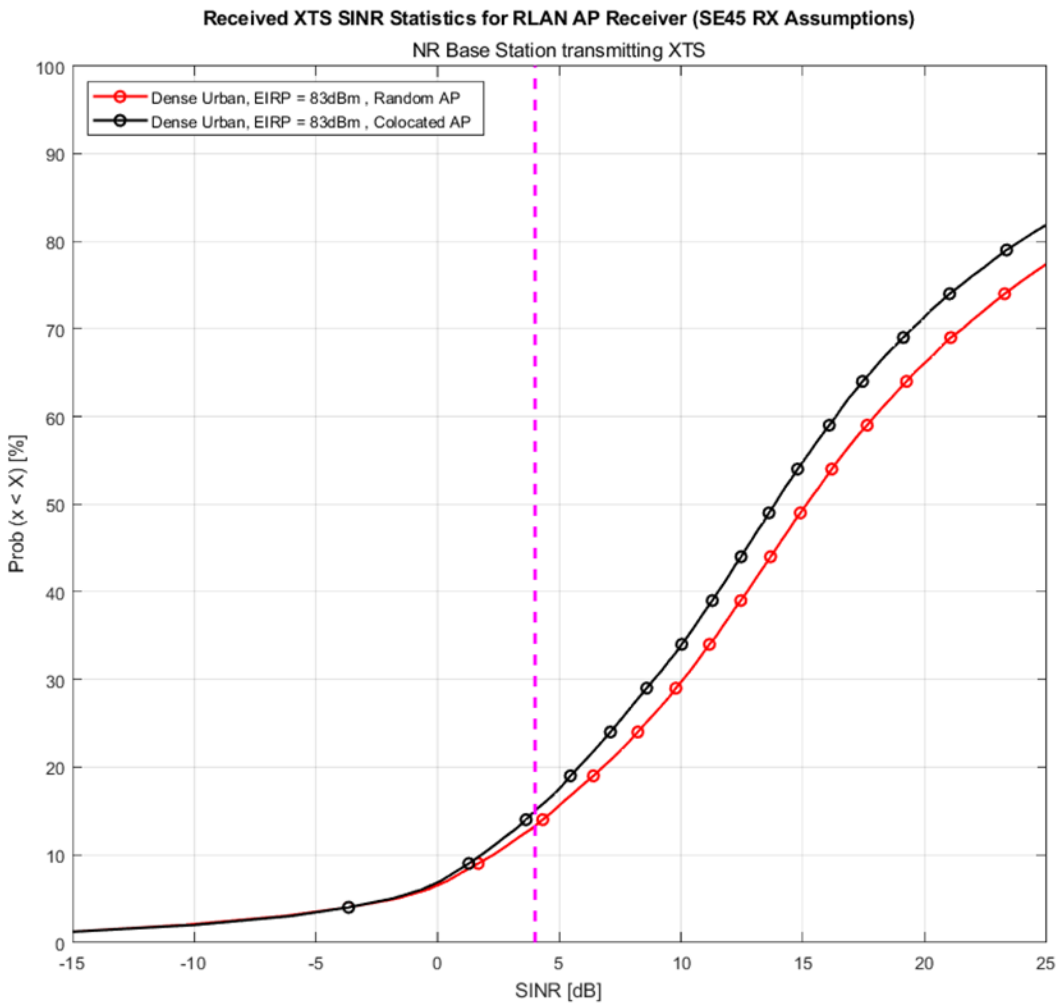


Figure 3-6: Cross technology signalling SINR statistics for IMT BS transmission

The first set of results shows expected **SINR** statistics for the baseline AP receiver using the parameters included in 3.2.1 along with the assumed SINR Threshold of **4 dB for** detection, shown in a magenta dashed line.

The different curves in the plots are differentiated by the choice of either random AP or colocated AP.

We can observe that:

- When the IMT BS transmits XTS using broadcast beam, the crossing with the SINR Threshold curve shows a probability of AP successfully decoding 802.11bc XTS signal around **85%.**
- Using broadcast beams for XTS transmission means that there is little to no dependency in the performance with respect to where the AP is located i.e. irrespective of if APs are randomly distributed or colocated, possibly only due to statistical differences in the distribution of the users.
- However, sharing results in the next sections will how the impact on IMT performance will differ depending on the choice of AP location.

The second set of results will show the statistics of the XTS received signal strength. Each scenario has two sets of curves:

- Solid curves: CDF of the received signal strength of the XTS transmission overall,
- Dashed curves: CDF of the received signal strength of the XTS transmission only if XTS SINR > SINR Threshold

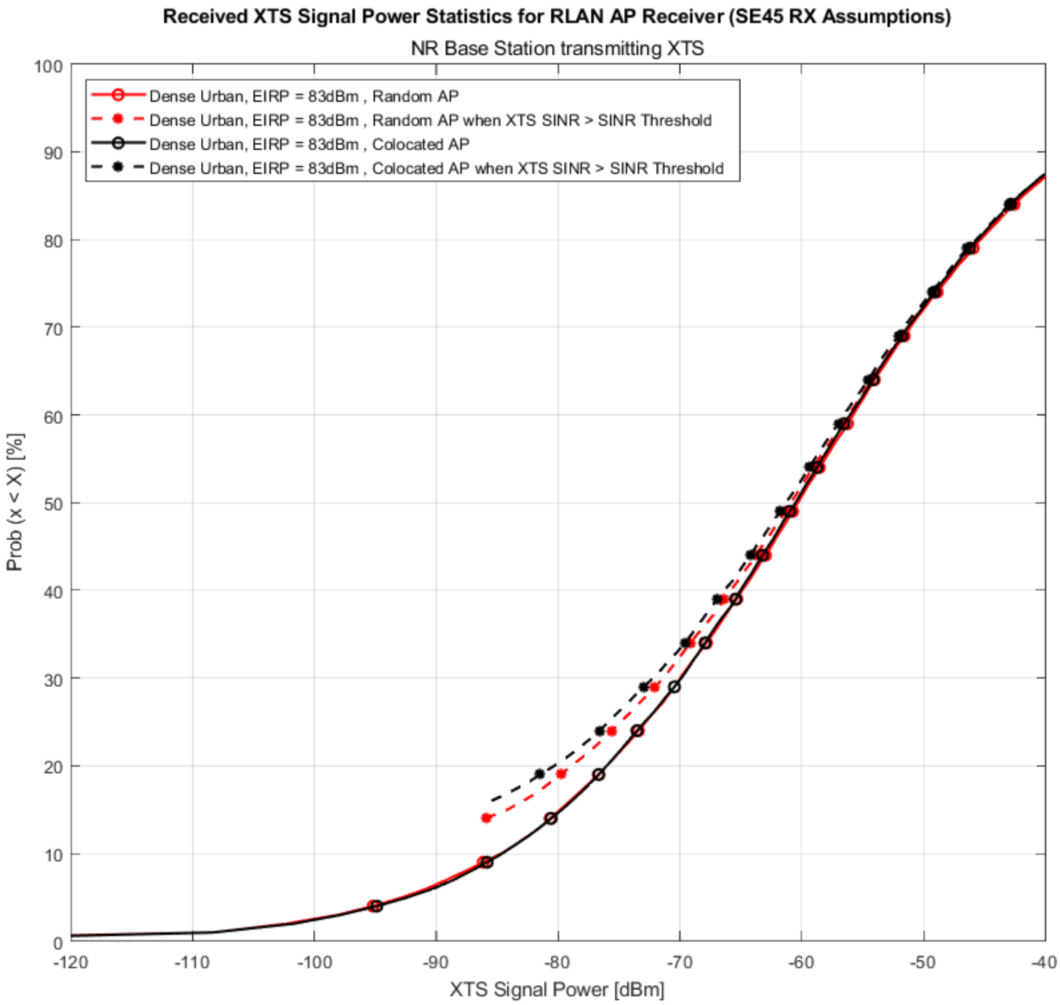


Figure 3-7: Cross technology signalling received power statistics for IMT BS transmission

The CDFs plotted with dashes lines represent for which power the given % of APs will successfully decode the XTS signalling in the simulation run and are included for information only. These curves can be useful to assess, in the case in which the Wi-Fi AP is assumed to vacate based on a received signal strength threshold, what percentage of Wi-Fi APs will be vacating the channel. The remaining APs will either not be able to decode XTS or receive it with a power below threshold.

The gap between solid and dashed curves shows the impact of the interference on XTS transmissions. A smaller gap means performance is noise-limited, and thus lower interference impact.

3.3.4 XTS Performances: IMT User Equipment as Source

This section presents one set of simulation results for the Cross Technology Reception statistics at the AP, assuming the IMT User Equipment is transmitting XTS.

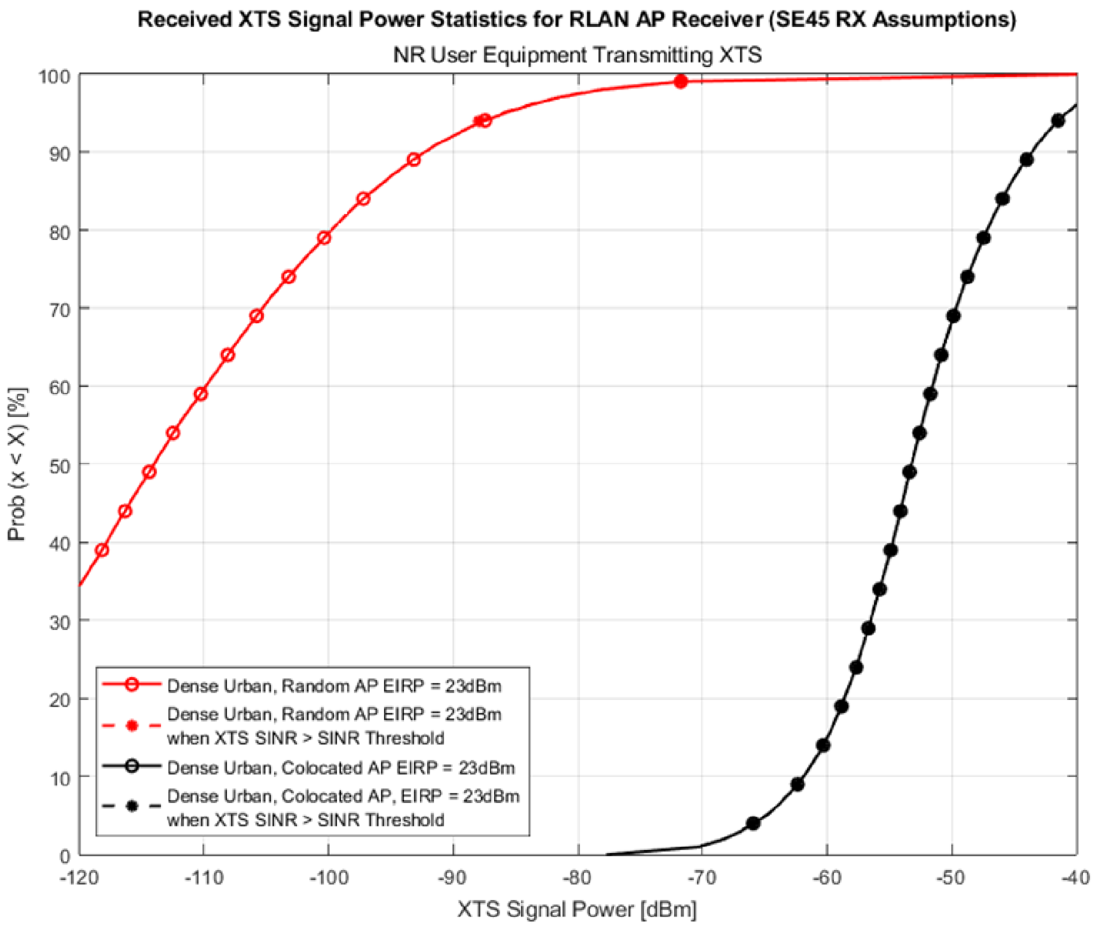


Figure 3-8: Cross technology signalling received power statistics for IMT UE transmission

The XTS power statistics show that:

- in the case of random deployments the dashed curve (CDF when XTS is larger than the SINR threshold) starts at a probability of around 95%, which means that there's only a likelihood of 5% for Wi-Fi APs to detect randomly located IMT UE XTS.
- In case of colocated AP instead the dashed curve starts from 0%, which means that the probability of a colocated AP detecting a UE XTS above the SINR reference is 100%. This should not be very surprising, as we can expect high likelihood of successfully receiving the signalling if the devices are located in close proximity.

- As both dashed and solid curves overlap, this means that there is no impact from interference coming from other UEs transmitting XTS.

3.3.5 Sharing: Impact to IMT DL Throughput from Active RLAN AP Deployments

This section focuses on the impact on IMT DL throughput degradation due to the presence of RLAN interference. For this part of the evaluation, it is assumed that only **XTS signalling** from **IMT User Equipment** to active to mitigate the impact of RLAN interference. This is because the interference to IMT DL is typically dominated by RLAN devices near the victim IMT UEs, as baseline results in 3.3.2 comparing random and colocated Wi-Fi APs for both DL and UL throughput.

The results included in this section will highlight the degradation we see in the simulations when both IMT and Wi-Fi deployments are active in the same location, and XTS is implemented to enable spectrum sharing and manage access to the channel.

During the execution of performance simulation assuming XTS, the implementation of the IMT system operation (cell selection, user scheduling, beamforming, etc) are execute in the same way as the evaluation in the baseline. The only exception is the transmission of the XTS resource, which will cause in every snapshot a number of Wi-Fi APs to vacate the channel and not contribute to the overall interference.

The different curves in the plots in this section are differentiated by the choice of different configurations:

- Wi-Fi AP and IMT UE location correlation: Random or Colocated;
- IMT/Wi-Fi Sharing: Use XTS, no XTS, IMT Only;

When XTS is active, the vacation policy is the following (*Always Vacate*): If the SINR of the XTS is above the SINR threshold, the Wi-Fi AP will always vacate the channel. Otherwise, it will transmit according to the assumptions.

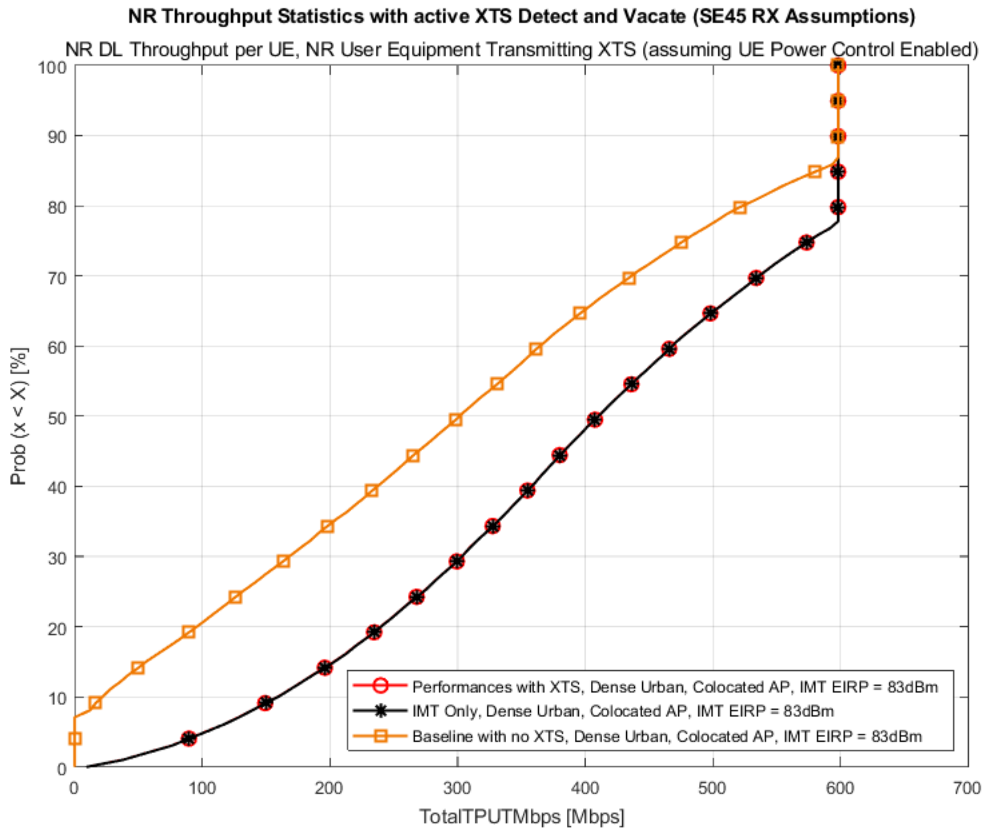


Figure 3-9: IMT DL Throughput performances with colocated AP with/without XTS and reference

The average number of active APs (not shown in the picture) in the simulation above when XTS is enabled is **0%**. This is because XTS is received with 100% probability when UE and Wi-Fi APs are colocated, so effectively all Wi-Fi APs have vacated the channel.

The results show that the modelled use of UE-based XTS for the case of colocated deployment ensures that **all** Wi-Fi APs vacate the channel, so in turn it is able to recover the same performance level as when IMT only is deployed.

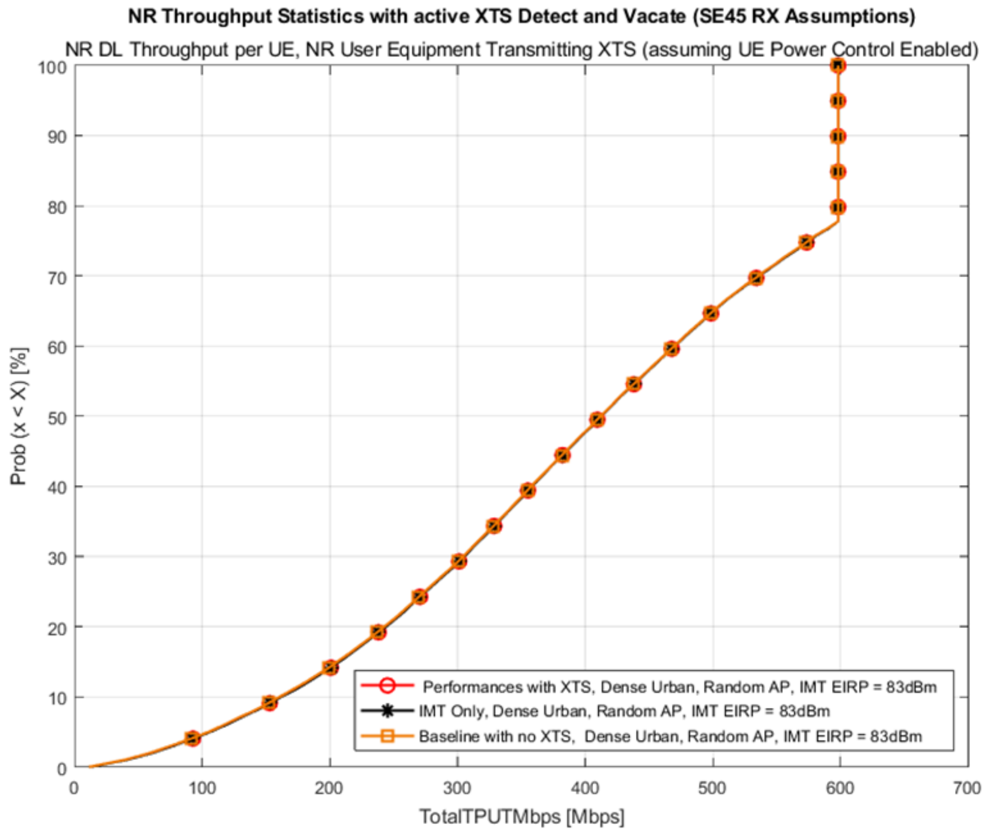


Figure 3-10: IMT DL Throughput performances with random AP with/without XTS and reference

The average number of active APs in the simulation (not shown in the picture) above when XTS is enabled is around **95%**. This is because XTS is received with 5% probability when UE and Wi-Fi APs are randomly located.

However, randomly located Wi-Fi APs only result in negligible impact to the DL performance, potentially due to the large difference in power received at the IMT UE between the IMT Base Station and the interfering Wi-Fi AP.

3.3.6 Sharing: Impact to IMT UL Throughput from Active RLAN AP Deployments

This section presents simulation results that show the impact of AP interference to IMT UL Throughput, in terms of statistical reduction, assuming **IMT Base Stations** are transmitting XTS signalling.

The different curves in the plots in this section are differentiated by the choice of different configurations:

- Wi-Fi AP and IMT UE location correlation: Random or Colocated;
- IMT/Wi-Fi Sharing: Use XTS, no XTS, IMT Only;

When XTS is active, the vacation policy is the following (*Always Vacate*): If the SINR of the XTS is above the SINR threshold, the Wi-Fi AP will always vacate the channel. Otherwise, it will transmit according to the assumptions.

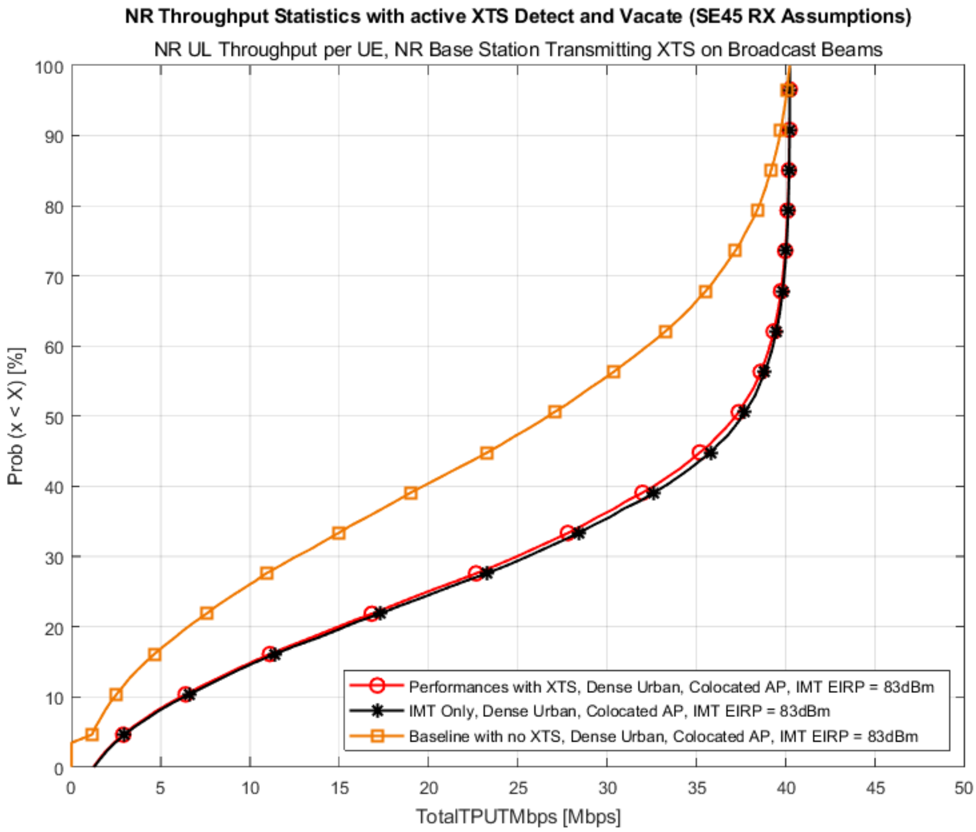


Figure 3-11: IMT UL Throughput performances with colocated AP with/without XTS and reference

The average percentage of active Wi-Fi APs (not shown in the picture) in the simulation results above when XTS is enabled is between **12-14**%. The residual interference from this quota of colocated Wi-Fi APs reduces the UL throughput by **0.5-1.5**%.

It is important to highlight that the simulation results do not include the potential further reduction of Wi-Fi AP activity achievable with the additional use of UE-based XTS. In that case, the percentage of Wi-Fi activity can be reduced to 0% (see Figure 3-9). This means that whenever IMT is deployed, Wi-Fi will not be able to use the band.

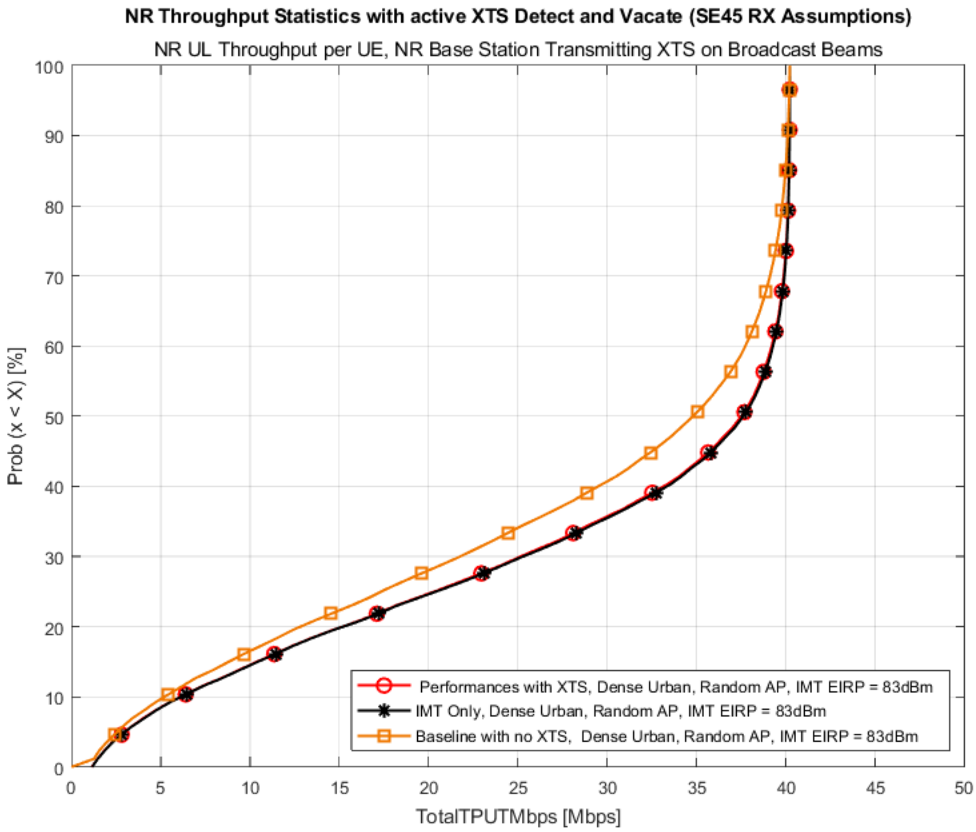


Figure 3-12: IMT UL Throughput performances with random AP with/without XTS and reference

The average percentage of active Wi-Fi APs (not shown in the picture) in the simulation results above when XTS is enabled is between **12-14**%. The residual interference from this quota of randomly located Wi-Fi APs only results in negligible impact to the UL performances.

3.3.7 Observations on Sharing Results: IMT protection and Wi-Fi footprint trade-off

In general, the results show that considering only IMT Base Station XTS transmission with 83dBm EIRP in 100MHz, and assuming Wi-Fi APs always vacate the upper 6GHz channel after the reception of XTS, the quota of active Wi-Fi APs will be around **12-14%** of the deployed ones. This means that between 86% and 88% of APs will not be able to use the band in case of IMT deployment in the same geographical area.

The increase in interference from the active Wi-Fi APs remaining in the channel results in an average impact to throughput within **2**%, according to the system level simulations collected in this section.

However, it should be noted that these simulations provide only a preliminary characterisation of the sharing technique, and do not consider many aspects that are necessary to fully assess the impact of Wi-Fi interference to IMT, and viceversa. For example:

- Bursty interference: this type of interference behaviour, typical in presence of unlicensed Wi-Fi devices, can have an impact on performance that goes beyond the average reduction in SINR. As shown in WP1, IMT systems are not designed or optimized to operate in the presence of such an interference profile.

- Impact on IMT frame: many IMT procedures are based on the availability of control and/or feedback channels in precise time instances. If the channel is occupied by an interfering Wi-Fi AP, the entire transmission can be lost.
- Impact on IMT frequency allocation: The trade-offs imposed by the XTS transmission in the upper 6GHz band need to be further considered, in particular
- The use of a power threshold on XTS: More Wi-Fi APs can be allowed to operate if it is agreed that Wi-Fi APs do not vacate unless the XTS level does not exceed a power threshold. However, this will reduce the separation between the two deployments that XTS can guarantee, and cause more impact to both systems.

To properly study these impacts, in the future a characterisation of time-based IMT performance and impact from bursty Wi-Fi AP transmission might be required.

This study focused on network deployment assumptions based on current expectations from both industry and regulatory players, and did not consider specific profiles in traffic increase: while the results seem to suggest that cross technology signalling could be used to separate the deployments and enable spectrum sharing also for scenarios in which the density of IMT Base Stations and Wi-Fi AP is either higher or lower, the impact of the interference from the residual quota of Wi-Fi APs will have to be carefully evaluated.

One of the requirements was to consider *whether the solutions and technical conditions tested under WP1 could deliver improved spectrum sharing when compared to existing technical parameters and authorisation methodologies and/or existing real-world deployment*: **The results show that in case of deployment in the same geographical area (e.g. urban area), it is not possible to sustain good performance for both technologies without dedicated sharing techniques.** To ensure a consistent level of performance for IMT networks, it is necessary to vacate the band from all Wi-Fi transmissions which would impact IMT throughput. The proposed techniques represent a possible tool to achieve this behaviour. The adoption of XTS could allow the maintenance of adequate IMT performance at the cost of Wi-Fi usage of the band in an area with dense IMT deployment. It is worth noting that even to achieve this simple detect and vacate policy, additional challenges need to be addressed, as described in section 3.6.

3.4 Model extensions

3.4.1 Suburban environment

According to the assumptions included in Section 3.2.2 for Suburban IMT deployment, in this section we present some of the results for this extension.

This section only presents the impact of the suburban assumptions on the baseline results, comparing with the Dense Urban references presented in Section 3.3.2.

The comprehensive summary of the results generated for this scenario is provided in the data results collection.

The conclusions that can be drawn for the Suburban scenario do not substantially differ from the dense Urban Scenario. The main differentiator between the two deployments being the average larger separation between IMT UE, IMT BS, and Wi-Fi APs.

In the case of randomly located IMT UE and Wi-Fi AP devices, this results in a lower baseline level of inter-system interference. While for colocated devices the impact from Wi-Fi AP interference can be larger because of the lower level of IMT interference coming from other IMT Base Stations.

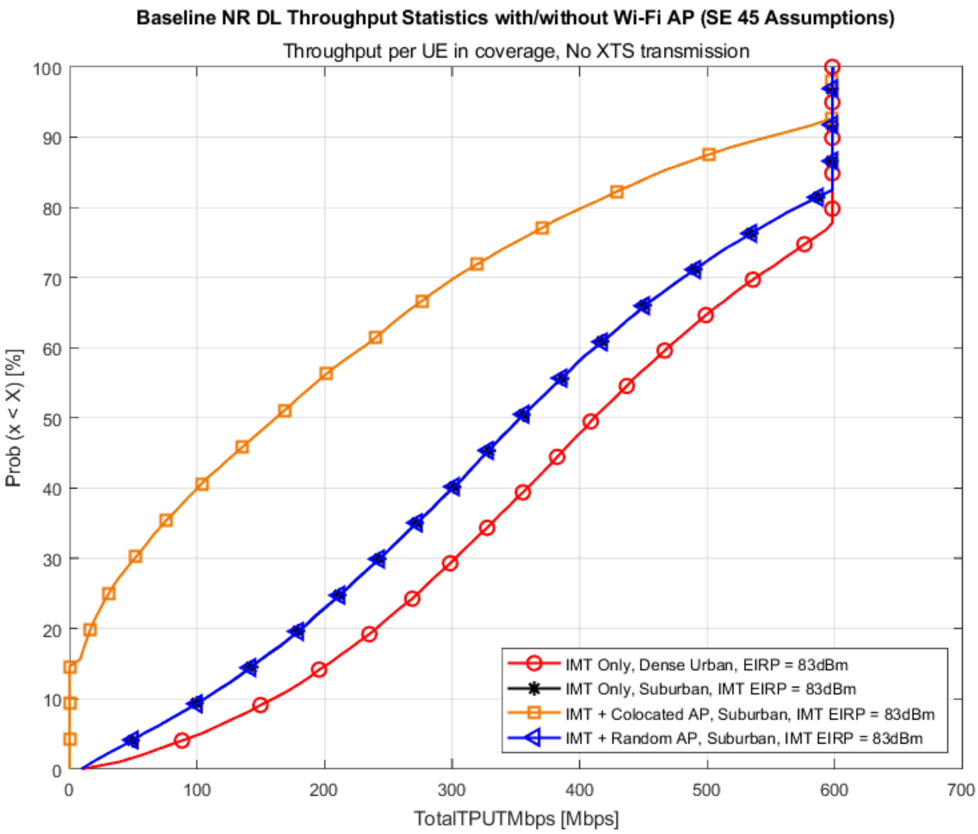


Figure 3-13: Reference IMT DL Throughput without sharing techniques in Suburban

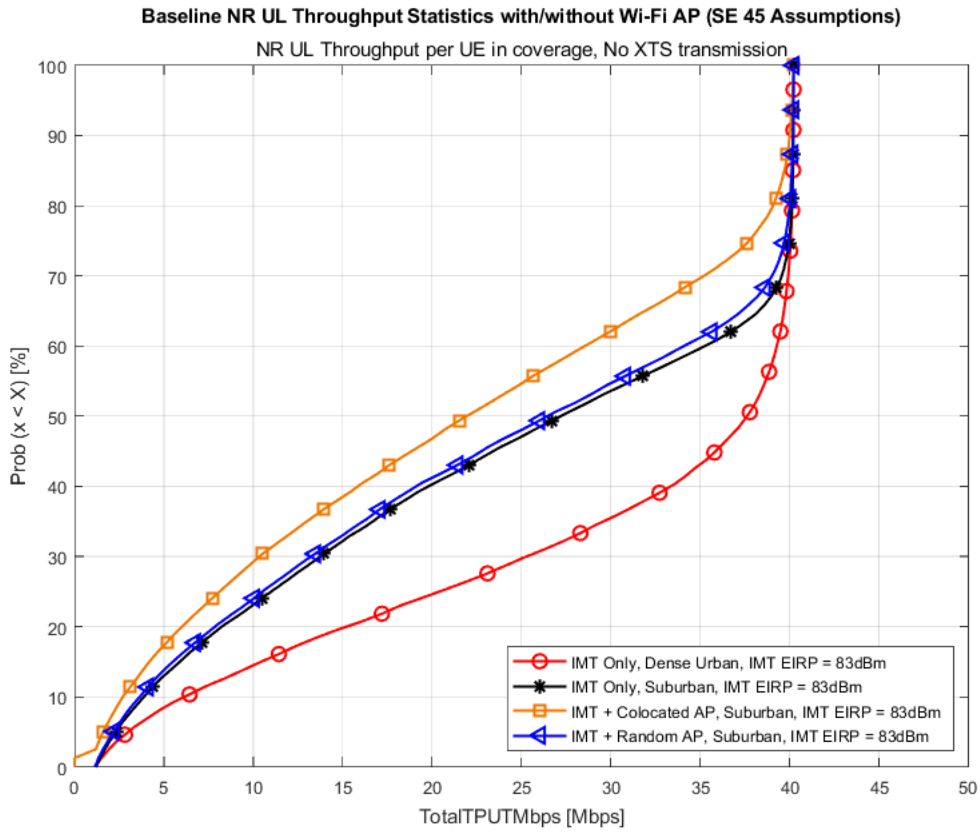


Figure 3-14: Reference IMT UL Throughput without sharing techniques in Suburban

3.4.2 BS EIRP: XTS Performances Impact

The results in this section show the impact of reducing BS EIRP on the performances of the XTS reception at the Wi-Fi AP.

Using the framework of the results already presented in Section 3.3, we present here a comparative analysis of the XTS SINR statistics for different EIRP values.

In particular, it is worth highlighting that:

- Reducing EIRP results in lower XTS performance, and the percentage of Wi-Fi APs that receive XTS with sufficient SINR for decoding decreases from **87%** for 83dBm EIRP to **52%** in the case of 58dBm EIRP.

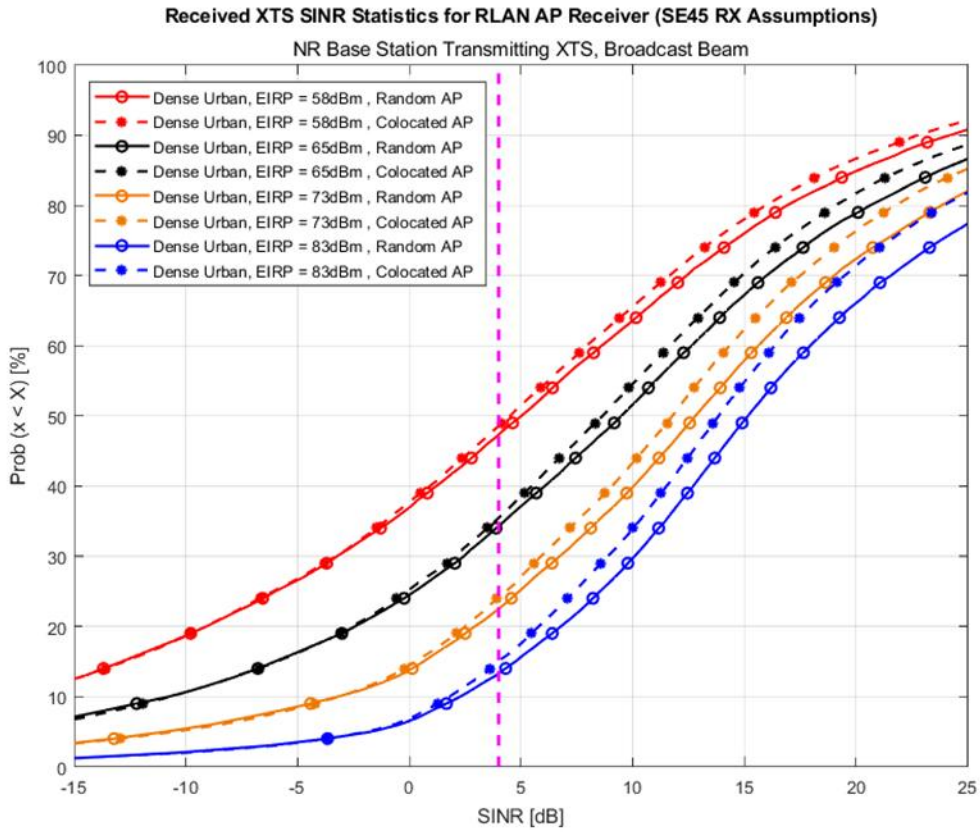


Figure 3-15: Comparison of XTS performances for different IMT BS EIRP levels

3.4.3 BS EIRP: Impact to IMT Throughput DL

The Impact on coverage caused by the varying EIRP powers is studied observing the following metrics for the Downlink Throughput analysis:

- The probability of Downlink SINR below the minimum SINR threshold, so Throughput = 0;
- The reduction in average Throughput;

From preliminary results, we observed that IMT performance is extremely sensitive to the maximum allowed peak EIRP in this scenario. In particular, reducing the peak EIRP causes substantial performance reduction to both indoor and outdoor users compared to standard levels expected for deployment in this frequency range.

However, it is important to note that the use of Montecarlo simulations cannot provide by any means a complete assessment of the impact of EIRP reduction on the IMT system performances. This is because, unlike typical spectrum coexistence evaluations which are routinely modelled with a reasonable degree of abstraction, the impact to many Key performance indicators (KPIs) such as IMT coverage, quality of service, and user experience are not captured when comparing these different options through Montecarlo simulations due to the many simplifying assumptions.

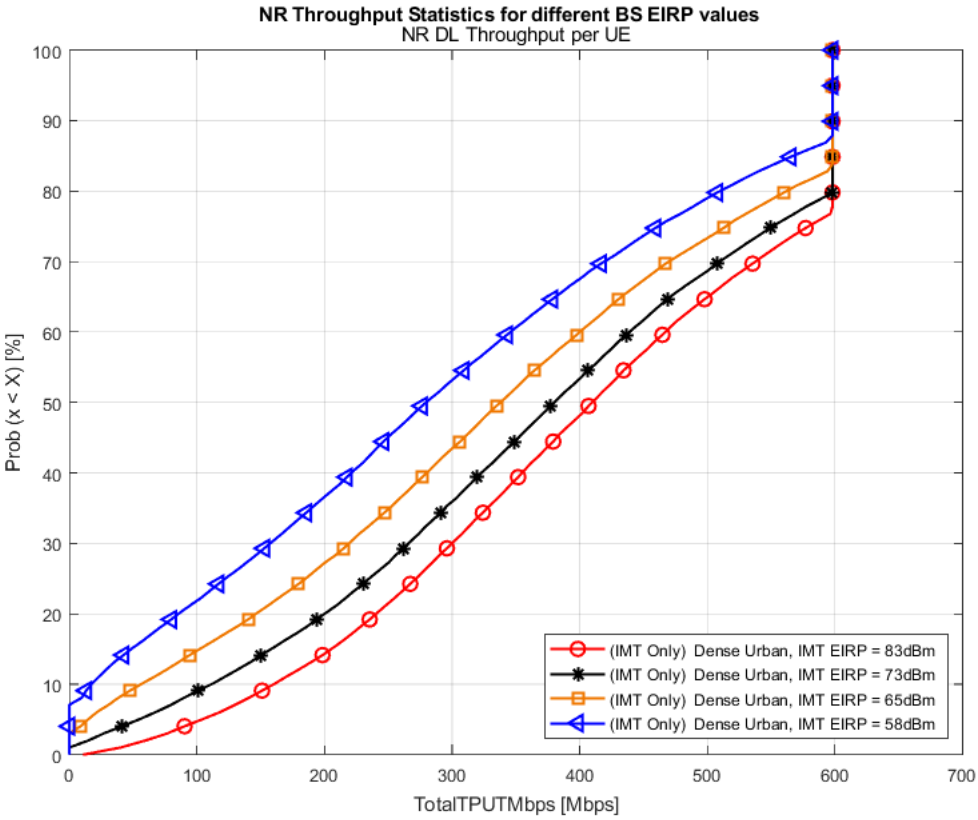


Figure 3-16: NR DL throughput statistics for different BS EIRP values

3.4.4 Coupling Loss Statistics for the XTS link with IMT Base Station as a Source

In this section we are presenting coupling loss (CL) statistics for the XTS link for the case in which IMT Base Station is transmitting XTS. These statistics are extracted from the results shown in Section 3.3.3.

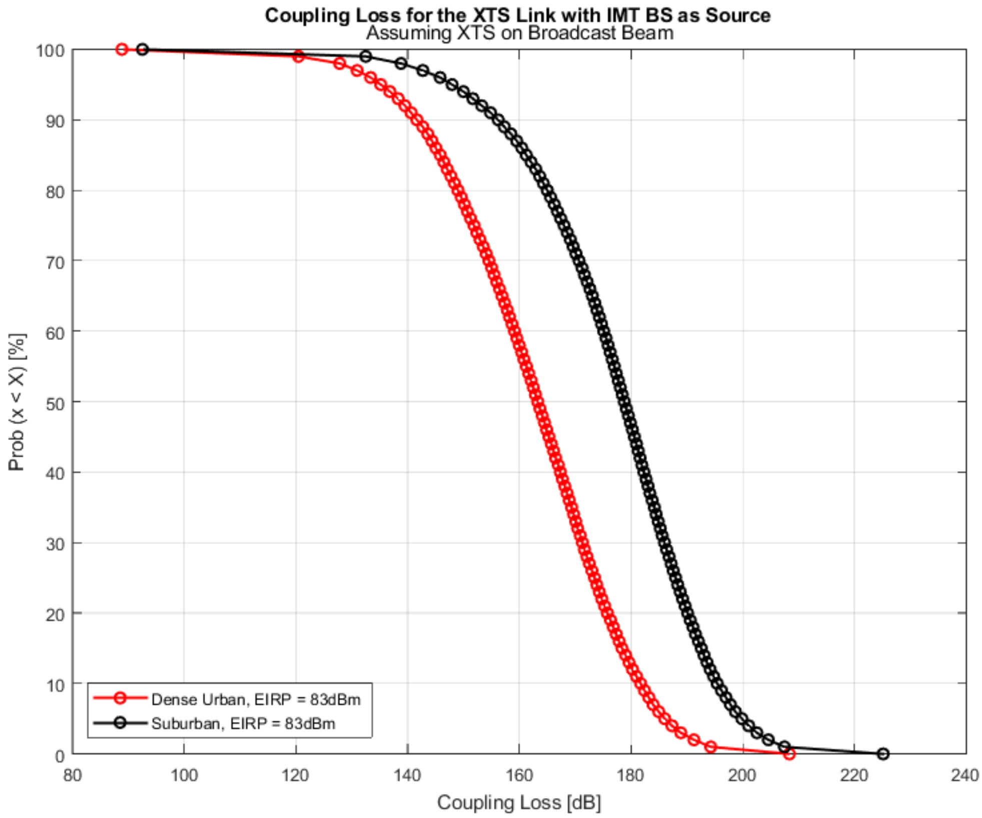


Figure 3-17: Coupling Loss for the XTS link with IMT Base Station as a Source

The results provide an overview of the expected coupling loss including all the modelling blocks (transmitter chain, path loss, penetration loss, receiver chain, etc), and can be used as a reference for alignment.

3.5 Concluding remarks and recommendations

In this study, we evaluated the feasibility of the cross-technology signalling concept as a means to facilitate sharing in the upper 6 GHz bands. This concept offers a mechanism for detecting the presence of mobile services in Wi-Fi areas. Once a mobile service is detected, mitigation measures can be activated to minimise service degradation caused by interference.

The observations provided above emphasise that defining a sharing solution between IMT and Wi-Fi involves several aspects that could determine the success or failure of the sharing approach. Given the complexity of the problem and the investment needed to develop such solutions, it is fundamental that both the regulatory framework and required standards are in place before any device enters the market. The standards need to cover both technical minimum requirements and associated conformance testing. The standardisation process would also help technology stakeholders build confidence in the effectiveness of the sharing solution.

4. Independently operated private networks in the n77 band

4.1 Introduction.

We have developed a Monte Carlo simulator to emulate a private (or cellular network). The private network in this scenario consists of 20 sites or small cells, randomly distributed in an area (Figure 4-1). The average inter-site distance is approximately 500 m, but there may be neighbouring sites with distance less than this. The minimum distance allowed between two sites is 200 m. Each site is equipped with a 4T4R omni directional antenna, and we have distributed approximately 5,000 users in the area, from which we select randomly 5 of those for each small cell to be active.

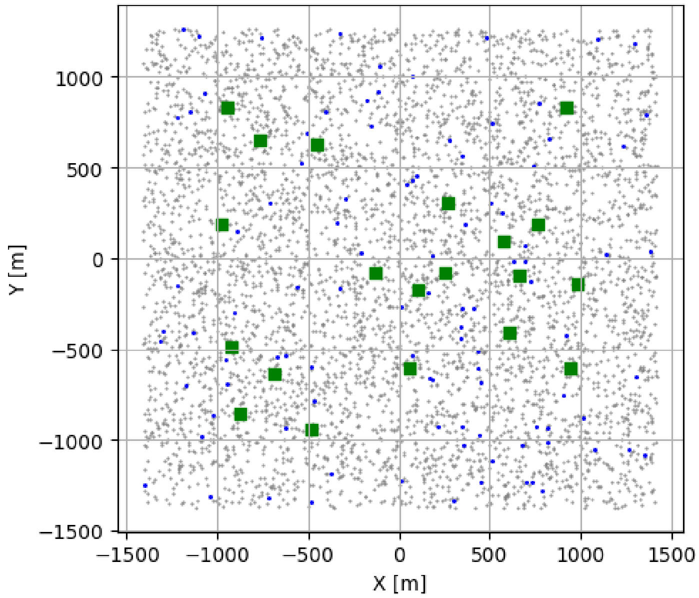
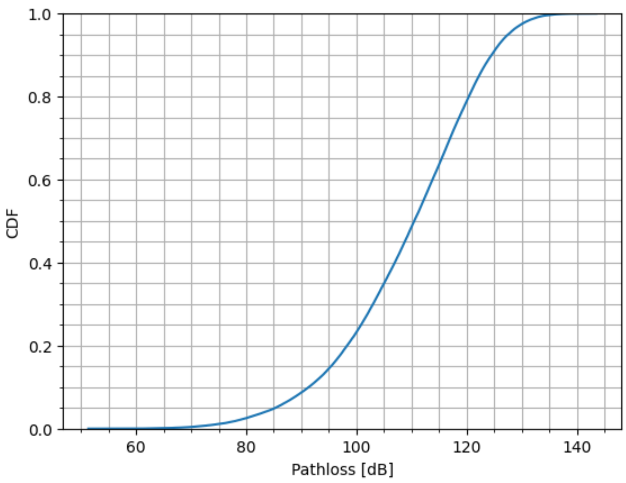


Figure 4-1. A random small cell network with 20 small cells and 1,000 UEs. At every site there are 5 active UEs, selected randomly (represented by the blue points).

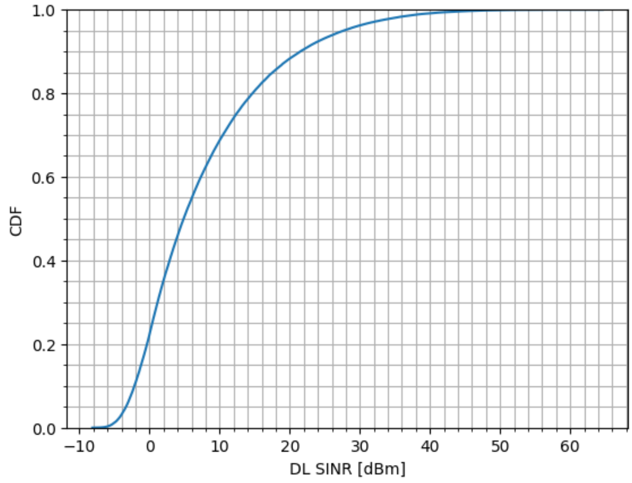
The omni antenna at each small cell site has a gain of 8 dB and it is at a height of 10 m, while we assume that the UE is equipped with a 4 element antenna (as the ones used in the measurements in Parson's Green) with a gain of -4 dB and a height of 3 m. The system operates in the 3.9 GHz band, with 100 MHz bandwidth.

For every set of parameters, we run the simulation for 1,000 iterations to gather statistically significant results. The randomness in this scenario lies with the location of the small cells, the location of the users within each cell, as well as the pathloss realisations, along with their characterisation as LoS or NLoS according to the generalised model's LoS probability.

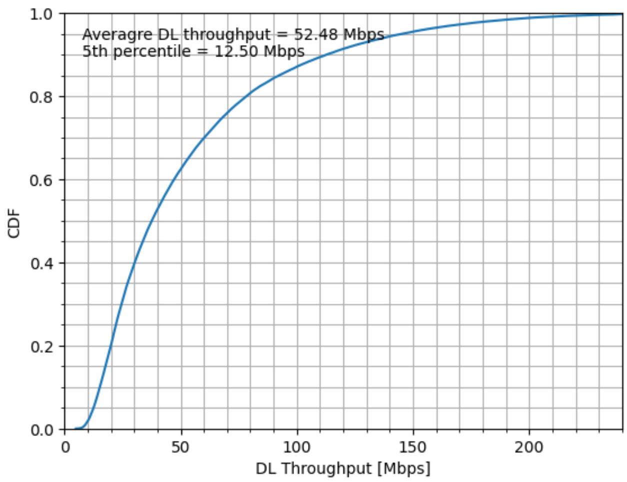
As an example, we show CDF graphs for such a network in terms of pathloss, SINR and throughput. We use the 3GPP 38.901 model to make pathloss predictions and the SINR-to-SE model to translate the signal quality to throughput.



(a)



(b)



(c)

Figure 4-2. (a) The pathloss CDF of the users, (b) the compute SINR CDF, (c) the CDF of the achieved throughput.

We introduce an aggressor network, operating at the same frequency and the same bandwidth, which, depending on the spatial separation from the victim network, can cause harmful interference and degrade the victim's network performance. We assume that the aggressor network has the same configuration parameters as the victim network – number of sites, transmit powers, antenna heights – and additionally, we assume that the two networks operate with the TDD method, and their frames are synchronised in time and in slot characterisation (UL/DL). Consequently then, the effects of the victim network to the aggressor network are similar to the effects from the aggressor network to the victim, and therefore, we perform the impact calculation on the victim network only. Furthermore, due to frame synchronisation, there is no interference between the base stations in the two networks. Finally, we assume that there is only one interfering (aggressor) network.

We present an example of such an aggressor network in Figure 4-3 in a close proximity to the victim network.

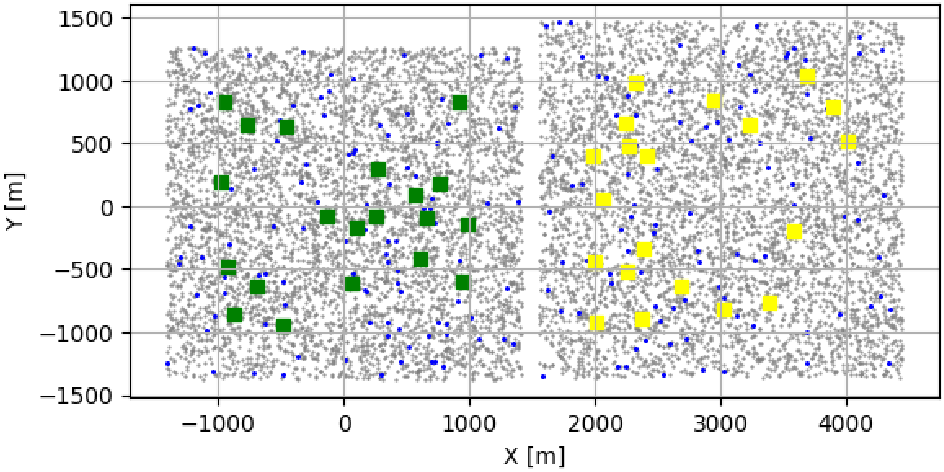


Figure 4-3. Adding an aggressor network (yellow squares) at a distance from the victim network (green squares). The blue dots are the active UEs in each network, randomly selected from all the available UEs.

The presence of the aggressor network increases the interference to the victim network, the impact becomes more severe as the distance between the two networks decreases. For every scenario we run, we record the interference-over-noise (I/N) ratio that every UE experiences (Figure 4-4). The interference in this case is the additional interference to each UE due to the aggressor network. In the example graph in the figure, the aggressor network is located 10 km away from the victim network, and it therefore does not cause any serious interference to the victim network.

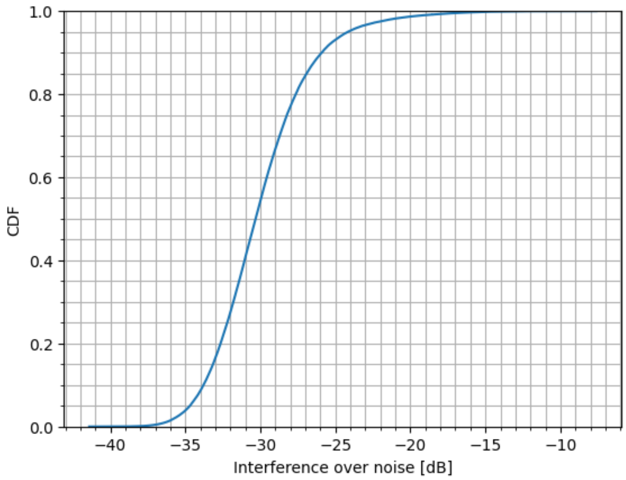


Figure 4-4. The I/N values at the UEs of the victim network, for the interference from an aggressor network which is located 10 km away from the victim network.

Overall, by changing the distance between the two networks, we can provide three key insights:

1. What is the minimum separation distance before the victim network experiences performance degradation, and
2. What is the minimum separation distance before the victim network experiences performance degradation above a certain level that is deemed acceptable.
3. How does that compare against the target set by Ofcom.

In the latter step, there are two aspects that we need to consider; the first one is what would be the separation distance with respect to the strict sense of the I/N target, while the second aspect is what would be the expected outcome if Ofcom had done this analysis. We need to acknowledge that Ofcom's procedure is a semi-deterministic one, and as such, it is dependent on the location that this process is applied at. Additionally, the model that Ofcom uses in its analysis differs from the generalised one, as well as from actual measurements, and it therefore introduces a level of inaccuracy. For these reasons, we offer an indicative expected spatial separation based on results published by Ofcom.

Ofcom published examples of sterilised areas in [2]. In the first example, a 20 m transmitter, radiating at medium power, is located at Newmarket and the sterilisation area assuming UEs at 3 m and I/N target of 0 dB (this is the "Alternative option B") is calculated (Figure 4-5). The sterilisation area corresponds to the locations where the I/N is greater than the target. This is not uniform around the transmitter due to the environmental obstructions (buildings, trees, hills) that surround the transmitter and block the signal. In this example, we can see that the limit of the sterilisation area is approximately 6 km away from the transmitter.

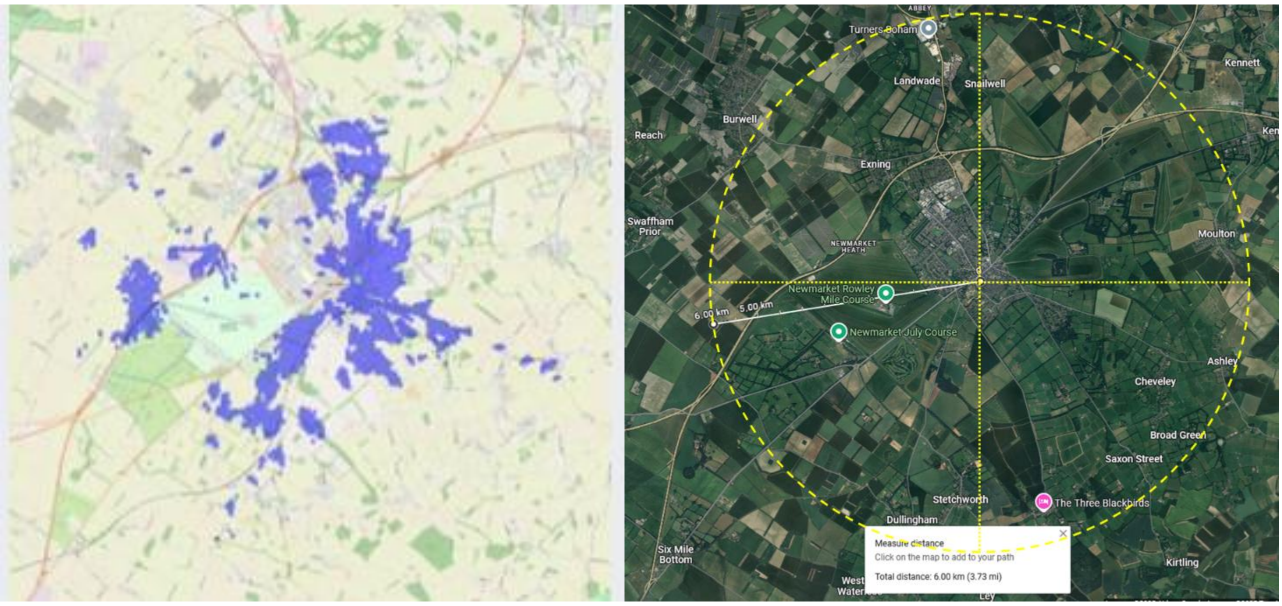


Figure 4-5. Medium power rural outdoors sterilisation area at Newmarket [2]. The transmitter is at 20 m and the receiver is at 3 m, while the I/N target is 0 dB. For comparison purposes, the sterilised area could be thought of as a circle with 6 km radius, which encloses the majority of the sterilised area.

In order for us to have a correspondence between the results of our platform and Ofcom, we run a simulation scenario where we calculated the effects between two networks with 20 base stations and the same configuration as in Ofcom's example, with variable distance[2]. The results show that at a distance of 6 km, the victim network experiences a 0.3% I/N violation, meaning that, on average, 0.3% of the active UEs encounter an interference level from the aggressor network, equal or greater than the target (Figure 4-6). Therefore, when reporting the separation distance using different metrics, we estimate Ofcom's expected distance based on that level of I/N violation.

[2] As distance between the two networks, we consider the minimum spatial separation between any two base stations of the two networks.

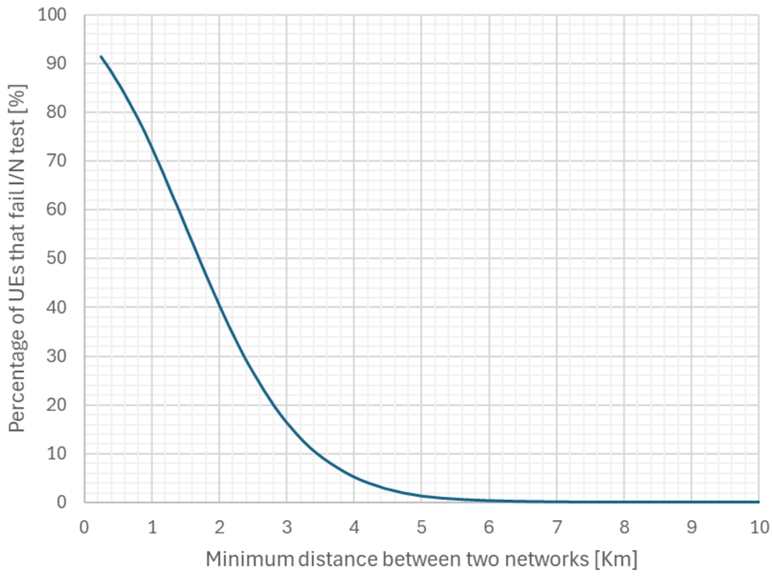


Figure 4-6. The calculated I/N percentage violation between two networks, operating in medium power and in a rural setting, with respect to distance.

We acknowledge that this is not a strictly accurate generalised value, as it is valid for that specific location, for which Ofcom provided the analysis – the ITU-R P.452 model is location specific. Nonetheless, we will use that limit as an indicator of the separation distance that could be reported by Ofcom.

4.2 Simulation Parameters

We present the main simulation parameters for this scenario in the table below.

Table 4-1. The simulation parameters for the independently operated private networks in the n77 band. These parameters are valid for both n77 networks, victim and aggressor.

5G-NR		
	Base station	**User equipment**
Frequency band	n77 [3.85 GHz]	
Bandwidth	100 MHz	
Numerology	1	
Percentage of UE outdoor	100 %	
Duplex method	TDD	
Directional resource split [15]	75%/25% [DL/UL]	
Number of sites/users	20	5,000 (5 active per small cell)
EIRP/Transmit power [16]	Low power: 34 dBm Medium power: 49 dBm	21 dBm
Antenna type	Omni	Omni

Antenna height	10 m [2]	3 m [17]
Antenna gain	8 dBi	-4 dBi [15]
Antenna downtilt[3]	6°	0°
Number of antennas	4	4
Noise figure	7 dB	10 dB [2]
I/N target	0 dB [2]	
Propagation loss model	3GPP TR 38.901	
Environment type	Urban: Urban microcell (UMi)/Street canyon Suburban: Urban macrocell (UMa) Rural: Rural macrocell (RMa)	

4.3 Model results and extensions

This section includes the simulation results for the coexistence of two n77 private networks and the effects on service performance. We have simulated two power levels (low and medium power), as well as three environment types – urban, suburban, and rural.

4.3.1 Urban environment

In the following table (Table 4-2), we summarise the simulator outcomes for the required separation distance between two networks operating in n77, for low and medium power, while the rest of the parameters are as defined in Table 4-1. For the second column, '*Separation distance (km) - I/N target [Ofcom]*', we estimated the expected Ofcom distance based on the I/N violation percentage of 0.3%, which we use that value as an indicator.

The separation distance between the two networks needs to be greater if the base stations transmit with medium power, when the I/N target is considered, 1.55 km for the low power case and 3.85 km for the medium power one.

However, if we allow a level of service degradation, the separation distance can be decreased – the higher the percentage of the service degradation permitted, the shorter the required separation distance between the two networks.

In such a case, the separation distance is not affected by the transmit power levels of the two networks. The reason for that is due to the fact that the increased power for both networks increase the wanted and the unwanted signals equally, and therefore in the majority of cases, the SINR remains unaffected. This is true because the size of the networks is small, and therefore we are not coverage limited, which may have been the case for networks with larger inter-site distances.

Table 4-2. Separation distances for between two low and two medium power n77 private networks, with respect to I/N targets and percentage of coverage degradation of the 20 Mbps service in urban area

Power level	Separation distance (km) - I/N target [Ofcom]	Separation distance (km) - 2% coverage degradation of the 20 Mbps service	Separation distance (km) - 5% coverage degradation of the 20 Mbps service	Separation distance (km) - 10% coverage degradation of the 20 Mbps service

[3] Request from Ofcom during one of our meetings.

Low power	1.55	1.3	0.68	0.28
Medium power	3.85	1.3	0.68	0.28

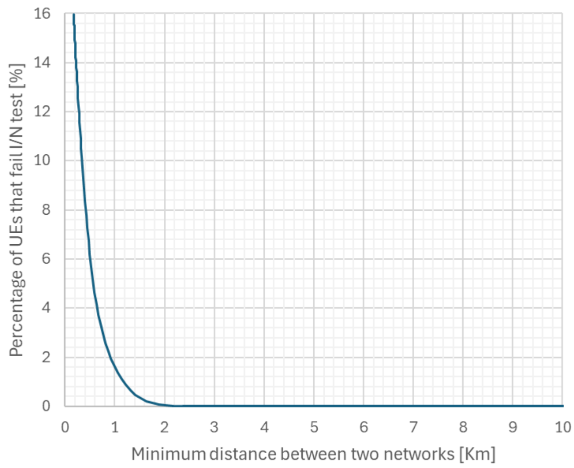
In the following subsections, we present graphs and more analysis on the outcomes.

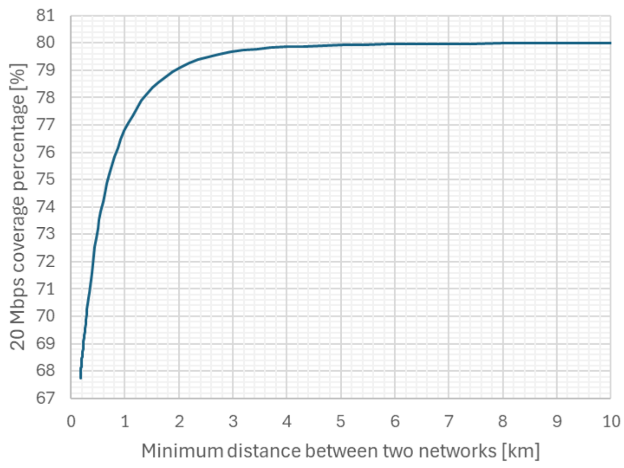
Low Power

Figure 4-7 shows the percentage of UEs that fail the I/N test and the coverage percentage of the 20 Mbps service in the victim network with respect to the distance of the aggressor network.

When the aggressor network is at a distance greater than approximately 4 km, the two networks do not interact, with the percentage of UEs that fail the I/N test being zero and the coverage degradation of the 20 Mbps service being minimal.

As the spatial separation between the two networks decreases, the impact of the aggressor network to the victim (and vice versa) becomes more prominent. At a distance of 1.55 km, where 0.3% of the victim networks UEs fail the I/N test, the 20 Mbps service coverage has been reduced by approximately 1.5%. However, if greater degradation is permitted, the spatial separation between the two networks can be further reduced, at 1.3 km for 2% degradation, 0.68 km for 5% degradation and 0.28 km for 10% degradation.





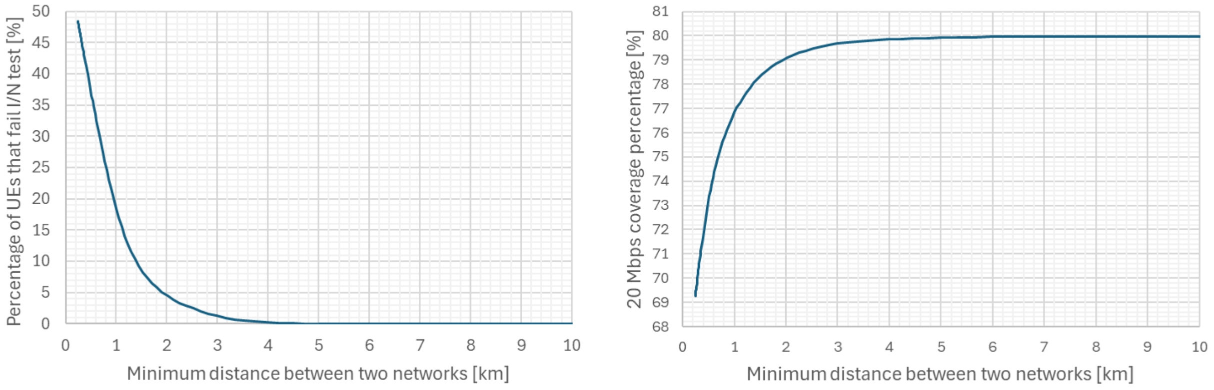
(a) **(b)**

Figure 4-7. (a) The percentage of users in the victim low power n77 network in an urban setting that fail the I/N target due to the presence of an aggressor network at a distance, and (b) the effects of the aggressor network on the 20 Mbps service.

We should note that a lower service, for example 2 Mbps, is more tolerant to interference due to the low SINR requirements. Therefore, the distance between the two networks can be further decreased, if the required guaranteed service is low (in this case the defining factor is not actually the service level, but rather the SINR target, as the service level depends also on the system's bandwidth).

Medium power

Similar comments as in the low power scenario are valid for the medium case. An important aspect to note is that the I/N violation percentage increases much earlier than the low power case – from about 4 km rather than 2 km for the low power networks (Figure 4-8). However, the 20 Mbps coverage follows the same degradation as in the low power example, due to the fact that the SINR values remain unchanged.



(a) **(b)**

Figure 4-8. (a) The percentage of users in the victim medium power n77 network in an urban setting that fail the I/N target due to the presence of an aggressor network at a distance, and (b) the effects of the aggressor network on the 20 Mbps service.

4.3.2 Suburban environment

When the two networks are in a suburban setting, the required separation distances between the two networks for the low and medium power cases become greater, when considering the I/N target, than in the urban environment, which means that in a suburban setting, signals travel slightly longer causing interference[4]. On the other hand, when considering the performance of the 20 Mbps service and different levels of coverage degradation, the required separation distance becomes slightly less than the urban scenario[5], leading to higher intensity of spectrum sharing.

Table 4-3. Separation distances for between two low and two medium power n77 private networks, with respect to I/N targets and percentage of coverage degradation of the 20 Mbps service in suburban area

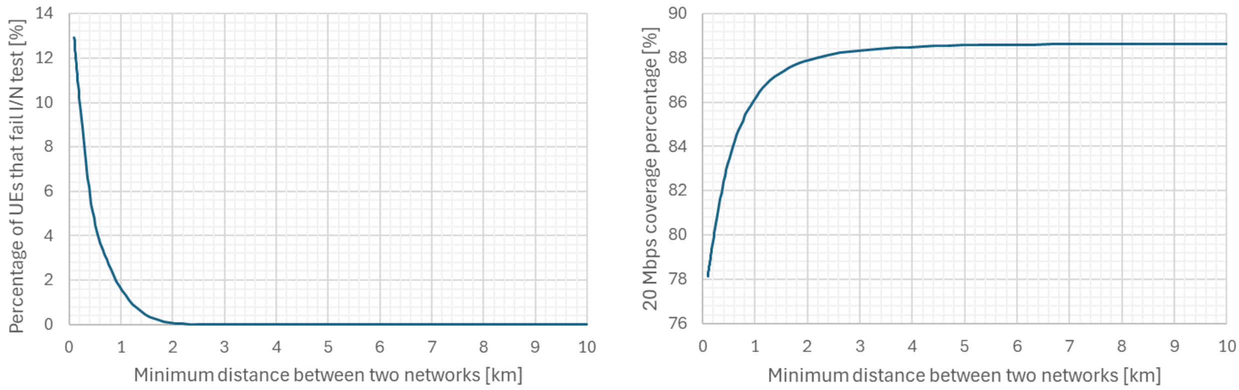
Power level	Separation distance (km) - I/N target [Ofcom]	Separation distance (km) - 2% coverage degradation of the 20 Mbps service	Separation distance (km) - 5% coverage degradation of the 20 Mbps service	Separation distance (km) - 10% coverage degradation of the 20 Mbps service
Low power	1.65	1.23	0.64	0.27
Medium power	4.2	1.23	0.64	0.27

In the following subsections we provide the graphs for the low and medium power for the I/N percentage violation and 20 Mbps service coverage.

[4] Strictly speaking, this is true for the LoS part of the 3GPP model between the urban (UMi model) and the suburban (UMa model) environment, which causes instances of higher interference, especially when the percentage of users that fail the I/N target is considered.

[5] This is due to the fact that, in contrast to the LoS case, the propagation loss of the suburban NLoS instances is higher than the one of the urban case, and considering that the majority of users are in NLoS, the overall effects on the suburban service is slightly less severe than the urban one.

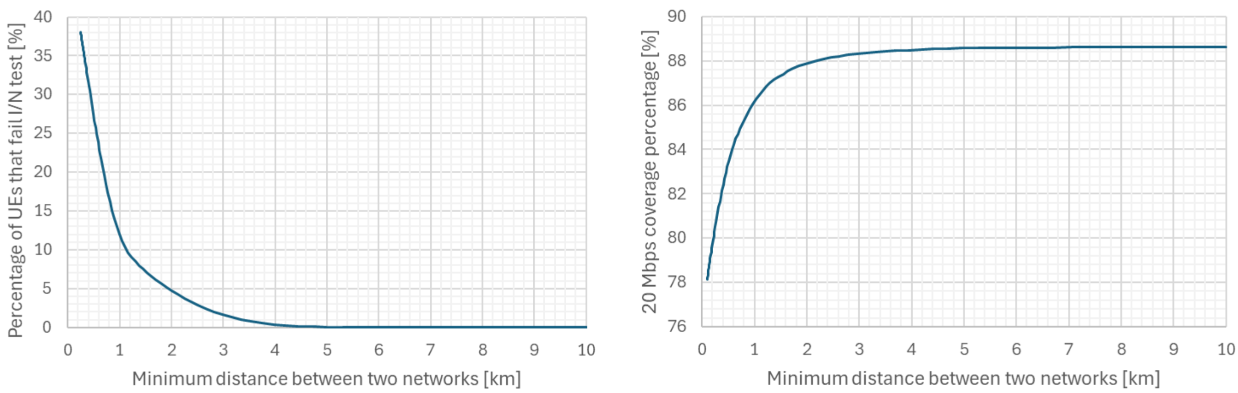
Low power



(a) (b)

Figure 4-9. (a) The percentage of users in the victim low power n77 network in a suburban setting that fail the I/N target due to the presence of an aggressor network at a distance, and (b) the effects of the aggressor network on the 20 Mbps service.

Medium power



(a) (b)

Figure 4-10. (a) The percentage of users in the victim medium power n77 network in a suburban setting that fail the I/N target due to the presence of an aggressor network at a distance, and (b) the effects of the aggressor network on the 20 Mbps service.

4.3.3 Rural environment

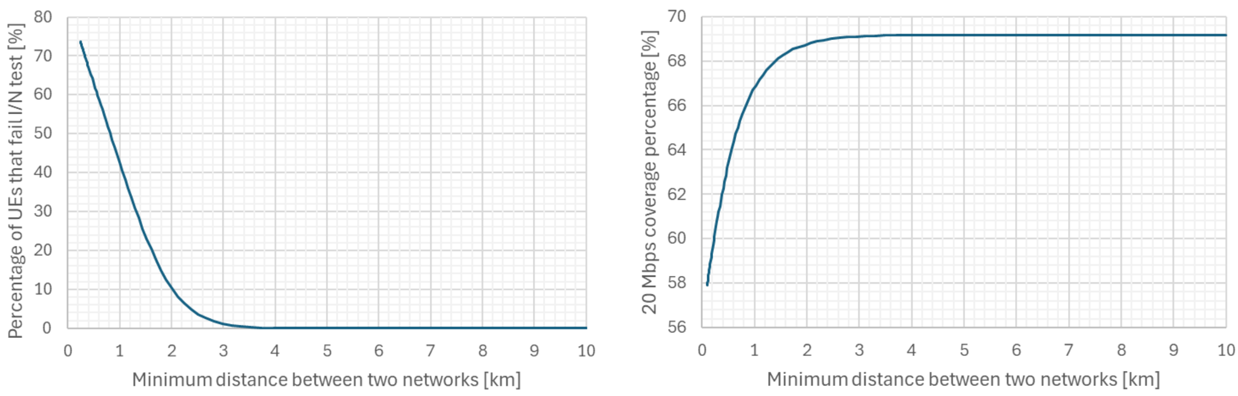
Finally, in a rural environment, the required distance due to the I/N target is approximately 3.5 km and 5.8 km for the low and medium power respectively. These distances are greater than the urban and suburban cases, due to the lower LoS losses in the rural environment.

Table 4-4. Separation distances for between two low and two medium power n77 private networks, with respect to I/N targets and percentage of coverage degradation of the 20 Mbps service in rural area

Power level	Separation distance (km) - I/N target [Ofcom]	Separation distance (km) - 2% coverage degradation of the 20 Mbps service	Separation distance (km) - 5% coverage degradation of the 20 Mbps service	Separation distance (km) - 10% coverage degradation of the 20 Mbps service
Low power	3.5	1.17	0.68	0.31
Medium power	5.8	1.17	0.68	0.31

In the following subsections we provide the graphs for the low and medium power for the I/N percentage violation and 20 Mbps service coverage.

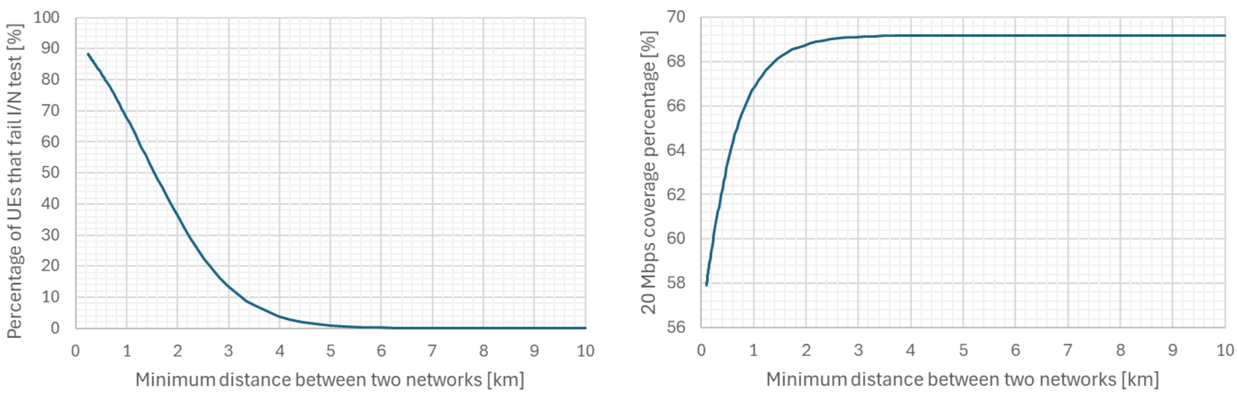
Low power



(a) (b)

Figure 4-11. (a) The percentage of users in the victim low power n77 network in a rural setting that fail the I/N target due to the presence of an aggressor network at a distance, and (b) the effects of the aggressor network on the 20 Mbps service.

Medium power



(a) (b)

Figure 4-12. (a) The percentage of users in the victim medium power n77 network in a rural setting that fail the I/N target due to the presence of an aggressor network at a distance, and (b) the effects of the aggressor network on the 20 Mbps service.

4.4 Recommendations for the potential to achieve more intensive sharing

This section analyses independently operated private networks in the n77 band and explores opportunities to enhance spectrum sharing. Our assessment reveals that there are opportunities to intensify spectrum sharing if it:

1. **considers the service requirements of the network users**: In the scenarios that we investigated, we demonstrate that we could reduce the spatial separation between two networks, without impacting the service performance.
2. **permits a certain level of performance degradation**: We could further reduce the distance between the two networks, if a certain level of performance degradation is permitted. Higher levels of allowed performance degradation led to higher spectrum intensity.
3. **models the wireless systems in the analysis**: It is more beneficial and accurate to model the actual networks, in terms of location and wireless configuration, to properly understand its performance and the impact of potential adjacent networks.
4. **uses accurate prediction models**: In our analysis we used the 3GPP TR 38.901 model, which is a general model, with limited input parameters. We can improve the spectrum intensity in the specific locations that we want to deploy new systems, by utilising more accurate prediction models. In such a case, large local obstructions will be part of the analysis, leading to improved sharing, but also in the absence of those, avoiding to negatively impacting the incumbent systems, by overestimating propagation loss and causing high interference.

5. Other technology pairs

This section explores how we could apply some of the principles and learnings from WP1 to additional technology pairs in other frequency bands. Note that many past coexistence studies have been conducted on these technology pairs for regulatory purposes. Therefore, our objective is not to conduct further exhaustive studies on these technology pairs. We limit our assessment to applying learnings from the sandbox experiments to benefit from them. We selected 3 additional technology pairs for this assessment:

1. Mobile and satellite – Direct to device (D2D) satellite in 2.6 GHz band
2. Mobile and airborne NTN
3. Mobile and fixed links in the upper 6 GHz band

4. As explained in Section 2, we have applied two key learnings from WP1, specifically:

   1. improvements in the channel model and
   2. mapping of Signal-to-Interference-plus-Noise Ratio (SINR) to throughput.

In Section 2, we concluded that the generalised channel models closely align with the measurements conducted in WP1. Therefore, for all mobile technology assessments in the aforementioned technology pairs, we utilise the generalised channel model. Additionally, we employ the SINR to throughput mapping model for both Mobile and Satellite D2D technology, as well as for Mobile and Airborne NTN.

The following sections provide our assessment of the potential for sharing for the three additional technology pairs we identified using the learnings from WP1.

5.1 Mobile and satellite: direct to device satellite in mobile bands

5.1.1 Introduction

In the case of mobile and satellite coexistence, we assume that this applies to Low Earth Orbit (LEO) satellites orbiting at a certain height (between 300 km to 1,500 km). The velocity of the satellite orbiting the Earth depends on its altitude. In the current scenario, we consider a LEO satellite, orbiting in a circular orbit. We display some of the parameters for modelling the satellite's orbit with respect to a location on the Earth's surface in the following (Figure 5-1).

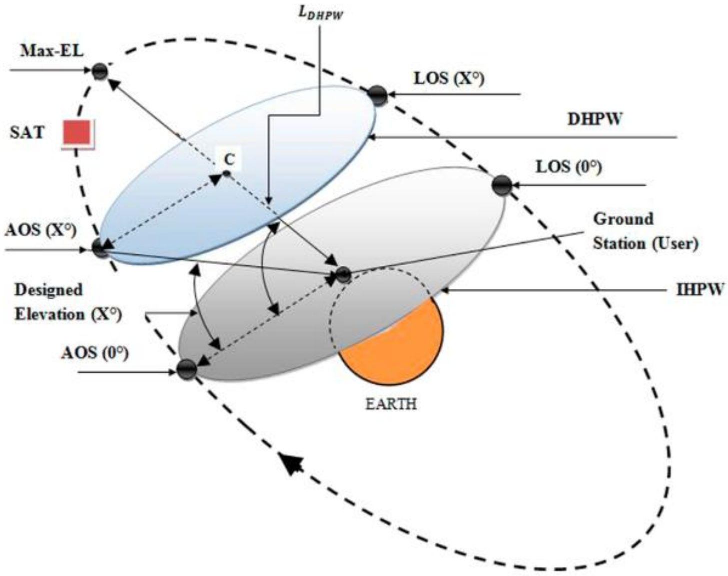


Figure 5-1. The *Acquisition of the Satellite* (AOS) and LOS angles define the horizon plane wideness, ideal (at 0°/180°) or designed at certain elevation angle X^0 (Source: [18]). If the user is in the flight path of the satellite, then max elevation angle is 90^0.

The LEO satellite is equipped with a large uniform planal array, and it generates a number of beams. It should be noted though that the more beams available, the wider the beam footprint (assuming a constant beam width). A typical value for the latter is between 100 and 500 km, depending on the altitude of the satellite and the number of beams.

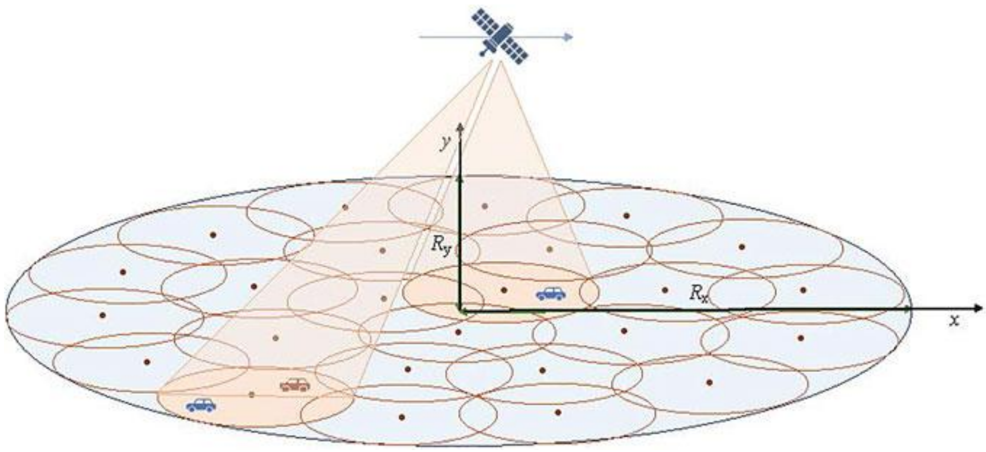


Figure 5-2. Beam generation from a LEO satellite (Source: [19]).

We assume that the overall beams' pattern projection on the earth surface is fixed, and it moves along with the satellite. That means that a UE connected to the satellite undergoes a number of beam handovers before the actual connectivity to the satellite is lost or switched to another satellite. The orbit of the satellite in our simulations moves along a north/south path and it crosses through the centre of the focus area of the terrestrial network (i.e. the maximum elevation angle is 90°).

In this scenario, we assume that the satellite is at an altitude of 525 km. A typical LEO constellation has 120 satellites per orbit [20], which equates to a beam pattern size of approximately 330 km (if we assume uninterrupted coverage along that orbital plane). Additionally, we model the antenna pattern for each beam as in 3GPP TR 38.811 with an aperture to wavelength ratio of 5.33 (Figure 5-3). We distribute the beams with 7° angular separation, so as to avoid cross-beam interference at the ground. Assuming that the satellite has 30 beams, the created beam pattern has an approximate size of 360 km, to allow for some level of overlap.

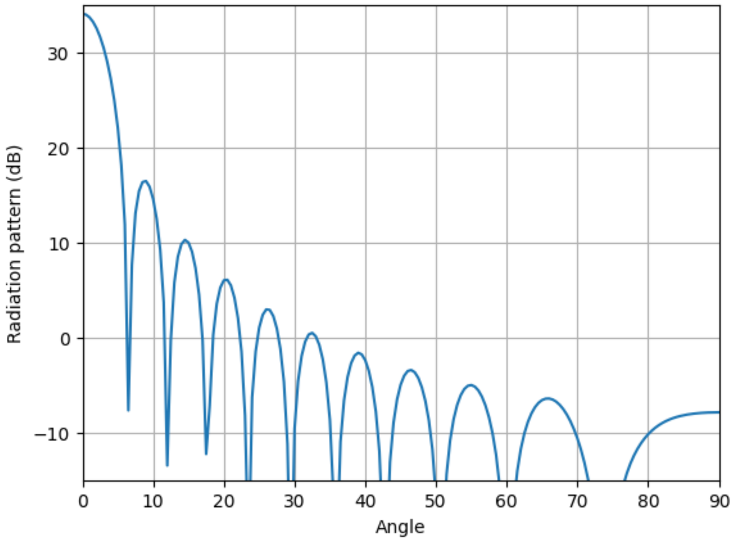
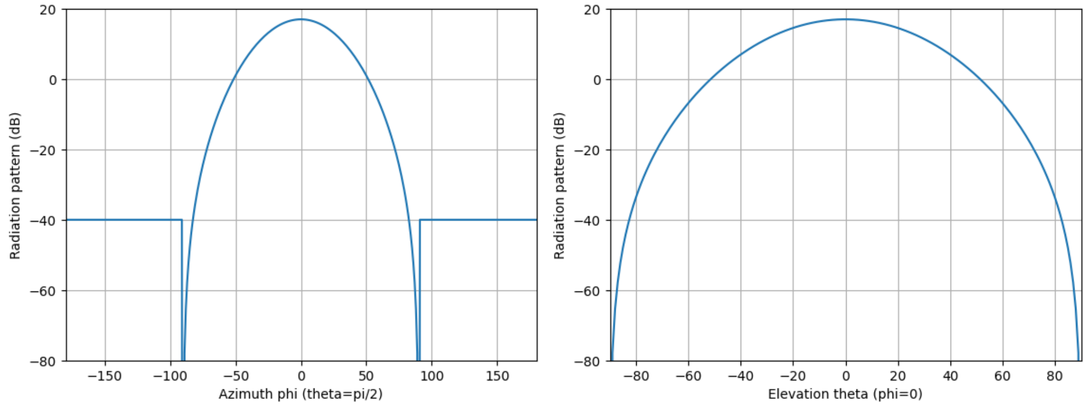


Figure 5-3. The pattern for a beam from the satellite. Maximum gain is at 34.1 dBi.

The UEs are connected initially to the terrestrial network. However, as the satellite moves closer and over the terrestrial network, the UEs may attach to it, if the signal conditions are better than the TN, otherwise, the satellite acts as an interferer.

The operating frequency of the mobile network is 2.6 GHz, and we assume that the MIMO antenna at each cell consists of 8 cross-polar elements [2x2x2] (Figure 5-3). Each cell generates beams towards each of the connected UEs using all the antenna elements. If the cell generates more than one beam, the transmitted power is divided equally to each beam. To avoid high inter-cell, cross-beam interference, we assume that users (and their corresponding beams) are 60° or more apart, otherwise, the users share that beam and its resources, while the algorithm places the beam to point between the UEs, to ensure a good performance for both users.



(a) **(b)**

Figure 5-4. The (a) azimuth and (b) elevation patterns of the main beam of the 2x2x2 antenna; 40 dB front to back ratio.

The satellite transmits signals with right-hand circular polarisation, while the UEs operate with linear polarization, and therefore we consider a 3 dB loss due to polarisation loss for the satellite to UE path.

We calculate the received signal strength from the satellite to the UEs using the 3GPP TR 38.811 pathloss model. Every UE is randomly assumed to be in LoS/NLoS with certain probability, relevant to each geotype and elevation angle (Table 5-1) – for example, at an urban environment, the lower the elevation angle, the higher the probability of the path between the satellite and the UE to be blocked by the surrounding buildings and other obstacles. For every elevation angle in our analysis, we use the information in the row that is closer to that value (as defined in the recommendation, i.e. we do not perform interpolation on the elevation angles that are between the entries of the probability table).

We plan the satellite system to achieve a central beam power flux density (pfd) of -83.5 dBW/m^2/MHz, which for a satellite at 525 km, it translates to an EIRP value of -78.88 dBm for signals with 5 MHz bandwidth.

For every point in the trajectory, we perform the calculations for 1,000 iterations, to gather statistics. We treat every point in the trajectory as an independent event.

Table 5-1. LoS probabilities according to elevation angle and environment type for satellite and airborne base stations.

Elevation	Urban environment	Suburban and rural environment
10º	24.6%	78.2%
20º	38.6%	86.9%
30º	49.3%	91.9%
40º	61.3%	92.9%
50º	72.6%	93.5%
60º	80.5%	94.0%

70º	91.9%	94.9%
80º	96.8%	95.2%
90º	99.2%	99.8%

We calculate the possible interference to the UEs of the terrestrial network from all the beams of the satellite. We further assume that if the propagation conditions towards the satellite are better than the terrestrial network, then UEs may attach to it. For the rest of the UEs, the satellite acts an interferer.

We calculate the I/N value at each UE location attributed solely to the satellite, and compare it with the I/N_{target} to assess whether the satellite would have permission to operate. For statistical confidence, we report the minimum distance that the I/N_{target} is violated for at least 0.05% of the UEs.

We also calculate the impact of the interference on the coverage of a 20 Mbps downlink service, and how the separation distance between the terrestrial network and the satellite can be reduced if we allow a certain level of performance degradation.

5.1.2 Parameters

The most common use case for satellite D2D communication is to provide coverage in mobile frequency bands where terrestrial coverage from IMT is unavailable. To reduce interference between the two systems, a significant separation distance is maintained between IMT and D2D deployments. The Federal Communications Commission (FCC) has established regulations for D2D communication through its Supplemental Coverage From Space (SCS)[21] initiative and Space Innovation regulations.

In the UK, sub-1 GHz bands are heavily utilised by mobile network operators (MNOs) due to the limited availability of spectrum in comparison to other bands. For this reason, we assume the use of the 2.6 GHz band for our simulations, as it is likely to be utilised less than the sub-1 GHz bands.

The major simulation parameters for the satellite system are in Table 5-2, while the simulation parameters for the terrestrial network are in Table 5-3.

Table 5-2. Parameters and assumptions for direct to device satellite systems

	Satellite
Constellation type	LEO
Altitude [ITU WP-4C Chairman's report, Oct]	525 km
Air interface technology	5G-NR
Frequency band	2.6 GHz
Bandwidth [ITU WP-4C Chairman's report, Oct]	20 MHz
Polarisation	Right-hand circular polarisation (RHCP)
Transmit EIRP	78.88 dBm
Antenna gain	34.1 dBi
Number of beams	30

Beam projection	Moving beams
Propagation model	3GPP TR 38.811

Table 5-3. Modelling parameters for the terrestrial network operating at 2.6 GHz [29]

5G-NR		
	Base station	**User equipment**
Frequency band	2.6 GHz	
Bandwidth	5 MHz	
Numerology	0	
Percentage of UE outdoor	100 %	
Duplex method	FDD	
Number of sites/users	19 (plus wrap around)	5,000 (3 active per small cell)
Intersite distance	Urban: 0.4 km Suburban: 0.8 km Rural: 4.0 km	N/A
EIRP/Transmit power	Urban: 59 dBm Suburban: 59 dBm Rural: 61 dBm	23 dBm
Antenna type	MIMO	Omni
Antenna height	Urban: 20 m Suburban: 25 m Rural: 30 m	1.5 m
Antenna element gain	8 dBi	-3 dBi
Antenna downtilt	Urban: 10º Suburban: 6º Rural: 3º	0º
Number of antennas	8 [2x2x2]	4
Noise figure	7 dB	9 dB
Body loss	0 dB	4 dB
I/N target	-6 dB	
Propagation loss model	3GPP TR 38.901	
Environment type	Urban: Urban macrocell (UMa) Suburban: Urban macrocell (UMa) Rural: Rural macrocell (RMa)	

5.1.3 Model results and extensions

We have summarised the calculated separation distances for the different targets in Table 5-4, while in the following subsections, we present the results in more detail.

When reporting on a separation distance, we consider this as the arc length on the surface of the earth between the centre of the terrestrial network and the nadir location of the satellite.

The results show that despite the large separation distance between the mobile network and the satellite, when considering the I/N target, for the urban and the suburban case, the impact of the satellite on the terrestrial 20 Mbps downlink service is almost minimal. The benefits for the rural case though are less prominent; the UEs experience interference that affects the service, but we can nonetheless achieve greater spectrum intensity if we allow for a greater level of coverage degradation (287.3 km for I/N-based separation distance vs. 183.3 km for 10% service coverage degradation).

Table 5-4. Separation distances between a terrestrial network and a LEO satellite, both operating in the 2.6 GHz band, with respect to the I/N target and percentage of coverage degradation of the 20 Mbps service.

Environment type	I/N separation distance [km]	Separation distance (km) - throughput measure (2% coverage degradation of the 20 Mbps service)	Separation distance (km) - throughput measure (5% coverage degradation of the 20 Mbps service)	Separation distance (km) - throughput measure (10% coverage degradation of the 20 Mbps service)
Urban	377.3	-	-	-
Suburban	287.6	102.3	-	-
Rural	287.3	224.5	212.5	183.3

Urban environment

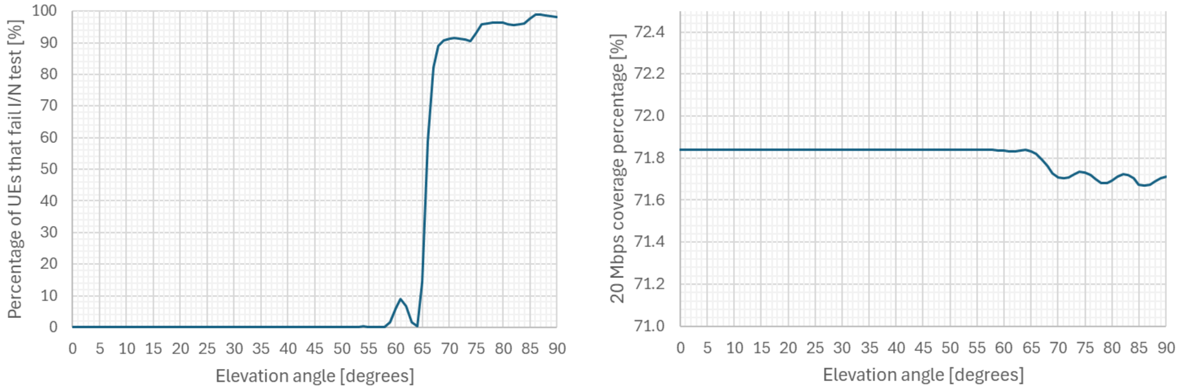
For low elevation angles, where the satellite is thousands of kilometres away, its impact on the terrestrial network is minimal. However, as the satellite nears the terrestrial network (i.e. the elevation angle increases), so is the interference that it causes to the terrestrial network. This is visible in Figure 5-5a, where the percentage of UEs that fail the I/N target increases. The small local peak at approximately 61° elevation angle is due to the first sidelobe of the first beam. There is a steep increase in the percentage at approximately 65°, as the network starts to become fully illuminated by the first satellite beam, closer to the mobile network.

The percentage creates a ripple effect with local maxima at approximately 71°, 79°, and 86° elevation angles, which correspond to the different satellite beams as the satellite's beam pattern transverses the network.

Even though the left-hand side figure implies a very high level of interference, the right-hand side (Figure 5-5b) shows that this effect is not severe. In that graph we show the coverage percentage of a 20 Mbps service in the terrestrial network, and how this is impacted by the presence of the satellite. It is expected that at low elevation angles, there will be no effect since the satellite is far away, while as the elevation angle increases, and the satellite directly transmits over the terrestrial network, the interference will be higher, and the service will reduce.

In this scenario though this expectation was not true, and the coverage of the 20 Mbps service was consistent during the whole flight of the satellite, with minimal impact (a maximum reduction of 0.17%). The main reason for this is that in the urban scenario, the inter-site distance between the base stations is 400 m, and therefore the UEs are in close proximity to their serving cells. They therefore experience high signal strength, as well as interference levels from the surrounding cells, at much higher levels than the additional interference from the satellite, which has then minimal consequence to the SINR levels of the UEs. This is corroborated by the fact that in our simulations there wasn't a single UE which experienced a better signal towards the satellite than the terrestrial network.

The outcome of this analysis is that for the urban scenario, a LEO satellite may not need to stop transmitting above the terrestrial network to avoid harmful interference, since it may not have an impact on its offered services. This though depends on the configuration of the terrestrial and satellite networks, and service requirements of the former, as we demonstrated for the parameters in this scenario.



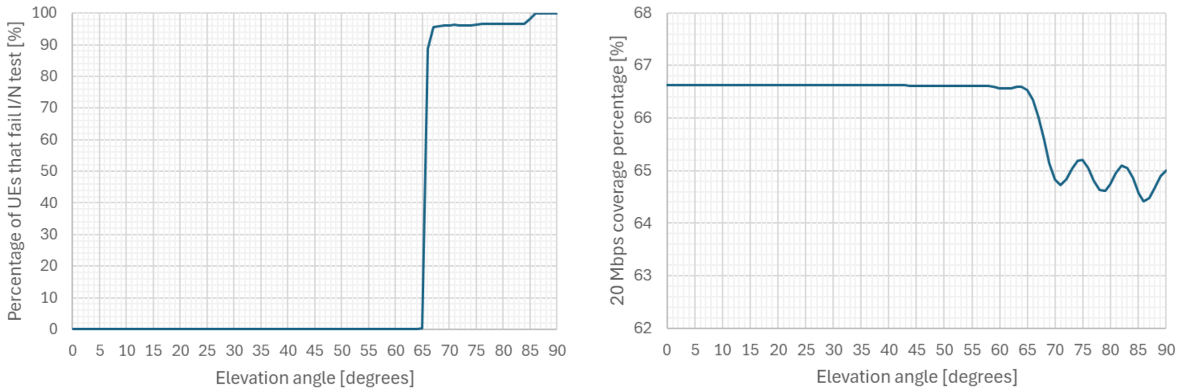
(a) **(b)**

Figure 5-5. (a) The percentage of UEs that fail the I/N target and (b) the coverage percentage of a 20 Mbps service vs. the elevation angle of the satellite platform in an urban environment.

Suburban environment

Similar comments to the urban scenario are valid for the suburban environment. The percentage of the UEs that fail the I/N target increases sharply at an elevation angle of 65°, where the first beam of the satellite illuminates the network (Figure 5-6a) and remains high as the satellite is above the terrestrial network.

The satellite's impact on the coverage of the 20 Mbps downlink service in the suburban scenario is greater than the urban case, but still not very severe (maximum degradation of 2.21%). Therefore, if coverage degradation greater than approximately 2% is permitted, then satellite and terrestrial networks can coexist without the need for spatial separation, in contrast to the 287.6 km separation required for conforming to the I/N target.



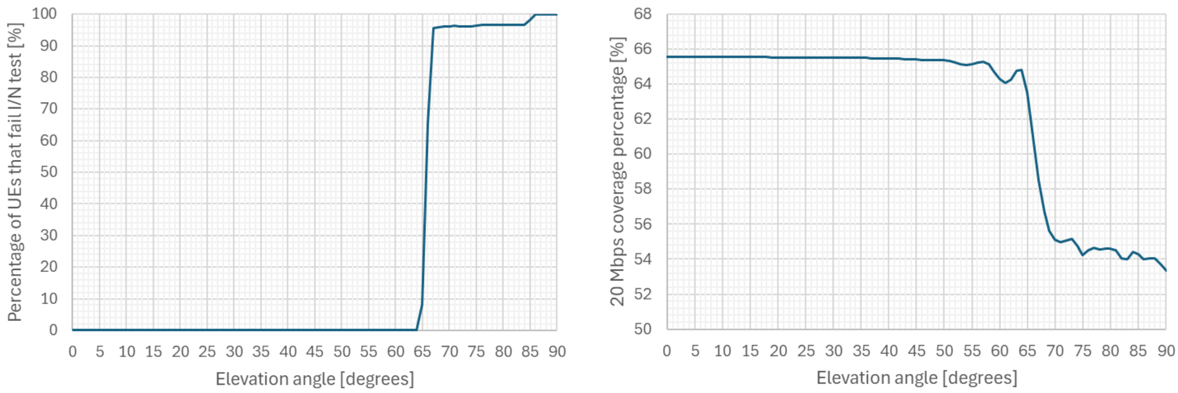
(a) (b)

Figure 5-6. (a) The percentage of UEs that fail the I/N target and (b) the coverage percentage of a 20 Mbps service vs. the elevation angle of the satellite platform in a suburban environment.

Rural environment

The rural scenario differs from the previous two ones (urban and suburban), due to its much greater intersite distance (4 km). The percentage of UEs that fail the I/N test is very similar to the suburban environment, demonstrating a sharp increase at an elevation angle of 64°.

However, the coverage of the 20 Mbps downlink service is more impacted by the satellite than the urban and suburban scenarios, even though the base stations in the rural environment transmit with 2 dBm more power. In the worst case, the service experiences a 12.16% coverage degradation due to the increased interference. This is supported by the fact that in the worst case, 22.47% of the UEs experience better signal from the satellite than the terrestrial network. Nonetheless, we can achieve greater spectrum intensity if we allow for a greater level of coverage degradation (287.3 km for I/N-based separation distance vs. 183.3 km for 10% service coverage degradation).



(a) (b)

Figure 5-7. (a) The percentage of UEs that fail the I/N target and (b) the coverage percentage of a 20 Mbps service vs. the elevation angle of the satellite platform in a rural environment.

5.1.4 Recommendations for the potential for more intensive sharing

In this technology pair, we have compared the separation distances between direct to device LEO satellite system operating in mobile bands and an IMT terrestrial network. Based on this analysis, we recommend that:

1. **Consideration of the wireless service requirement**: The I/N target may be a too conservative target, especially for systems that operate in very good wireless conditions (such as with high base station density). In such cases, the interference from the satellite is not of the same order as the interference from the surrounding base stations, and therefore it doesn’t impact the offered service, and the two systems can coexist.
2. **Permit a level of performance degradation**: We can reduce the separation distance between the satellite platform and the terrestrial network if we permit a certain level of performance degradation. The higher that level is, the greater the spectrum intensity.

5.2 Mobile and airborne NTN: airborne base stations in mobile bands

5.2.1 Introduction

This technology pair refers to the use of high-altitude platform stations as IMT base stations (HIBS) operating at heights between 8 km and 50 km. The airborne platform is equipped with a large planar array which allows it to provide more complex sectorised patterns through beamforming. The beam footprint size is typically between 5 km and 200 km.

This pair has great similarities with the mobile and satellite one, with the main difference being the altitude of the HIBS, which is much lower than the LEO satellites. Another difference is that the airborne base station is assumed to stay fixed in a location, and therefore, its beam projection also remains fixed relative to Earth, while the LEO satellite travels along its orbit.

To that extent, for the analysis for this scenario, we calculate the two dimensional (2D) distance separation between the mobile network and the HIBS platform to avoid any adverse interfering effects, considering the HIBS altitude and distance, as well as the environment type of the location where the mobile network is deployed, as this will affect the LoS probabilities (Table 5-1).

We then generate a mobile network with an average intersite distance and number of users, where an airborne base station is flying near or above the mobile network (Figure 5-8). For every set of parameters, we perform the calculations for 1,000 iterations to ensure statistical confidence.

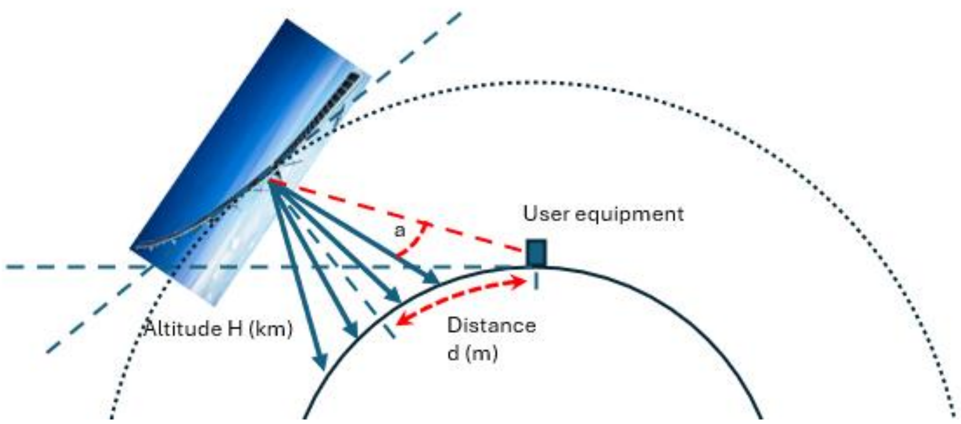


Figure 5-8. The interference between a terrestrial network and an airborne non-terrestrial base station operating in the 2.6 GHz band depends on their relative distance, deployment characteristics, altitude of the airborne base station, and service requirements.

We calculate the pattern for each beam as a reflector antenna with a circular aperture, which is approximated as the Bessel function of the first order with aperture radius of 1 wavelength. It creates a pattern with a 3-dB beamwidth of 30° and sidelobes which are 20 dB less than the main lobe (Figure 5-9). This calculation is part of [7], which we also use to calculate the propagation loss between the airborne platform and the terrestrial equipment.

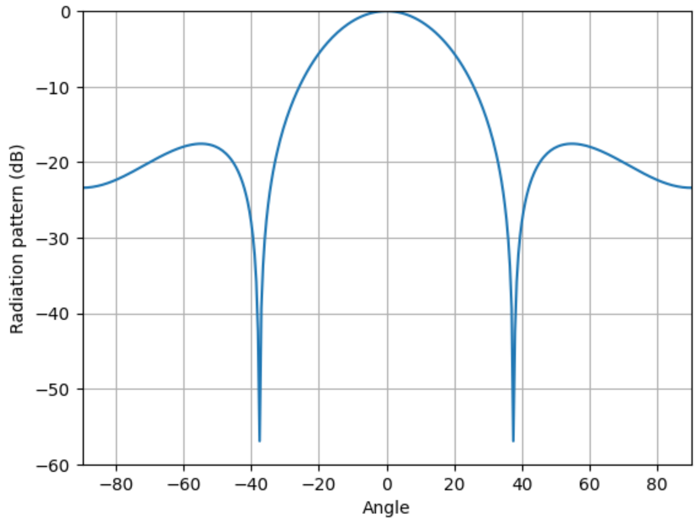


Figure 5-9. HAPS antenna, alpha/lambda = 1, 3 dB beamwidth = 30 degrees

The number of beams generated by the airborne platform is 7 – a central beam (layer 0) and 6 beams around that (layer 1) (Figure 5-10) at an angle of 60° [22]. The central beam points perpendicular to the earth surface below (the nadir direction).

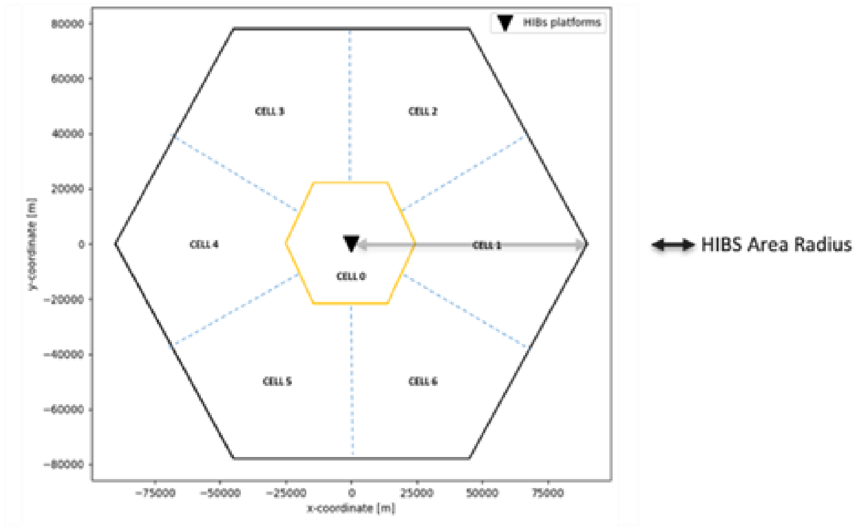


Figure 5-10. The beam pattern from a HIBS platform; 7 beams with the outer beams at a 60° angle from the main beam

We calculate the possible interference to the UEs of the terrestrial network from all the beams of the HIBS platform. We further assume that if the propagation conditions towards the airborne platform are better than the terrestrial network, then UEs may attach to it. For the rest of the UEs, the platform acts an interferer.

We calculate the I/N value at each UE location attributed solely to the airborne platform and compare it with the I/N_{target} to assess whether the airborne platform would have permission to operate. For statistical confidence, we report the minimum distance that the I/N_{target} is violated for at least 0.05% of the UEs.

We also calculate the impact of the interference on the coverage of a 20 Mbps downlink service, and how the separation distance between the terrestrial network and the HIBS platform can be reduced if we allow a certain level of performance degradation.

5.2.2 Parameters

The main simulation parameters for the airborne base station are in Table 5-5. The parameters for the terrestrial network are the same as in the 'Mobile and satellite: direct to device' technology pair (Table 5-3).

Table 5-5. Parameters and assumptions for high-altitude platform station as International Mobile Telecommunications (IMT) base station [28]

	Airbourne base station
Altitude	20 km
Air interface technology	5G-NR
Frequency band	2.6 GHz
Bandwidth	20 MHz
Polarisation	Cross-polar
Transmit EIRP	55 dBm
Antenna element gain	8 dBi
Number of beams	7
Beam projection	Earth fixed beams [7]
Propagation model	3GPP TR 38.811

Table 5-6. Parameters and assumptions for terrestrial IMT network

5G-NR		
	Base station	User equipment
Frequency band	2.6 GHz	
Bandwidth	20 MHz	
Numerology	0	
Percentage of UE outdoor	100 %	
Duplex method	FDD	
Number of sites/users	19 (plus wrap around)	5,000 (3 active per small cell)
Intersite distance	Urban: 0.4 km Suburban: 0.8 km Rural: 4.0 km	N/A
EIRP/Transmit power	Urban: 59 dBm Suburban: 59 dBm	23 dBm

	Rural: 61 dBm	
Antenna type	MIMO	Omni
Antenna height	Urban: 20 m Suburban: 25 m Rural: 30 m	1.5 m
Antenna element gain	8 dBi	-3 dBi
Antenna downtilt [29]	Urban: 10° Suburban: 6° Rural: 3°	0°
Number of antennas	8 [2x2x2]	4
Noise figure	7 dB	9 dB [23]
Body loss	0 dB	4 dB
I/N target	-6 dB	
Propagation loss model	3GPP TR 38.901	
Environment type	Urban: Urban macrocell (UMa) Suburban: Urban macrocell (UMa) Rural: Rural macrocell (RMa)	

5.2.3 Model results and extensions

We have summarised the calculated separation distances for the different targets in Table 5-7, while in the following subsections, we present the results in more detail.

When reporting on a separation distance, we consider this as the arc length on the surface of the earth between the centre of the terrestrial network and the nadir location of the airborne platform.

Table 5-7. Separation distances between a terrestrial network and an airborne platform, both operating in the 2.6 GHz band, with respect to the I/N target and percentage of coverage degradation of the 20 Mbps service.

Environment type	I/N separation distance [km]	Separation distance (km) - throughput measure (2% coverage degradation of the 20 Mbps service)	Separation distance (km) - throughput measure (5% coverage degradation of the 20 Mbps service)	Separation distance (km) - throughput measure (10% coverage degradation of the 20 Mbps service)
Urban	269.6	-	-	-
Suburban	180.7	46.4	6.4	1.6
Rural	179.7	126.1	78.9	47.2

Urban environment

In an urban environment, the required separation distance between the terrestrial network and the airborne platform is approximately 270 km (which corresponds to an elevation angle of 3 degrees).

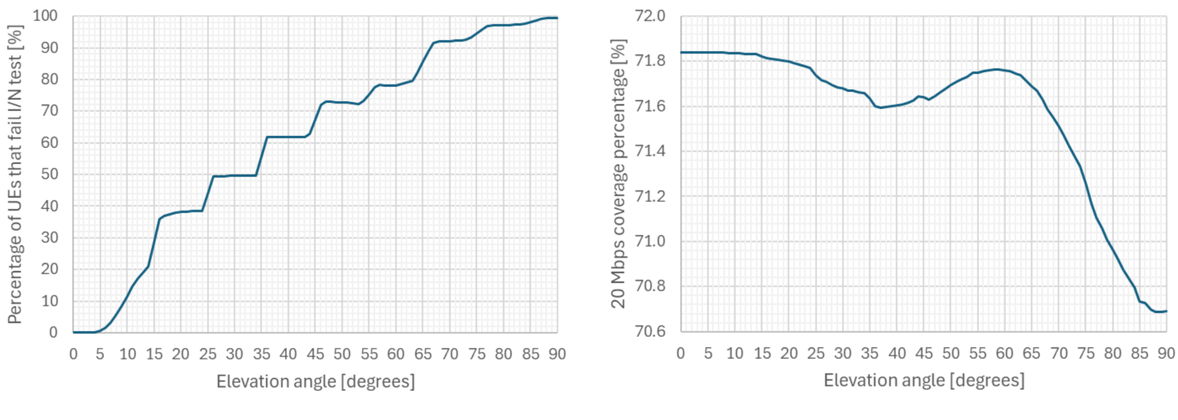
The percentage of UEs that fail the I/N target increases monotonically with the elevation angle in a steady manner (Figure 5-11a). This is mainly due to the fact that as the elevation angle increases, so does the probability of UEs being in a LoS state and therefore, higher probability of experiencing higher levels of interference from the airborne platform. When the HIBS platform is at 90^o elevation, almost all the UEs fail the I/N target (99.34%).

On the other hand, even though the interference from the HIBS platform increases and impacts more UEs, in terms of the I/N target however, this does not impact their overall performance. In Figure 5-11b, we can see that the percentage coverage of the 20 Mbps service reduces slightly even when the HIBS platform is directly above the cellular network (in which case the coverage percentage has reduced to less than 1.2%). This is because the intersite distance in this scenario is 400 m, and as a result, the UEs are very close to the serving base stations, experiencing high signal levels. Additionally, the major source of interference comes from the surrounding base stations, to which the interference from the HIBS platform has no severe impact.

That means that the airborne platform can be deployed simultaneously to the cellular network in an urban environment, without affecting the latter's performance.

The local peak value in the graph around the 60^o elevation angle corresponds to the elevation angle for which the terrestrial network is between the layer 0 and layer 1 beams of the HIBS platform (similar to its cell edge area). As the elevation angle increases and the layer 1 beam is moving away from the cellular network, the platform's layer 0 beam effects become more prominent.

Finally, the users very rarely had to connect to the HIBS platform instead of the terrestrial network. On average, at an elevation angle of 90^o, there were 0.043 users on average connected to the HIBS platform (that means that, in very few of the 1,000 instances, there were cases where the user connected to the HIBS platform).



(a) **(b)**

Figure 5-11. (a) The percentage of UEs that fail the I/N target and (b) the coverage percentage of a 20 Mbps service vs. the elevation angle of the HIBS platform in an urban environment.

Suburban environment

The separation distance between the terrestrial network and the airborne platform in a suburban environment is approximately 180.7 km (which corresponds to an elevation angle of approximately 5.5^o), when considering the I/N target.

This result seems to be at odds with the result for the urban case, where the separation distance is longer, since the expectation is the in an urban environment the losses will be higher, and therefore, the separation distance will be shorter. This is due to the propagation model used in the analysis, 3GPP TR 38.811, where, despite the losses for the non-line-of-sight path, which indeed are higher for the urban environment than the suburban one, the LoS signals exhibits greater variability (higher standard deviation) in the urban scenario, and as a result, higher probability of invalidating the I/N target (even considering that in an suburban environment, it is 3 times more probable to have a UE in LoS state than in the urban environment). For reference, we display the standard deviations and clutter loss that are applied for very low elevation angles in Table 5-8.

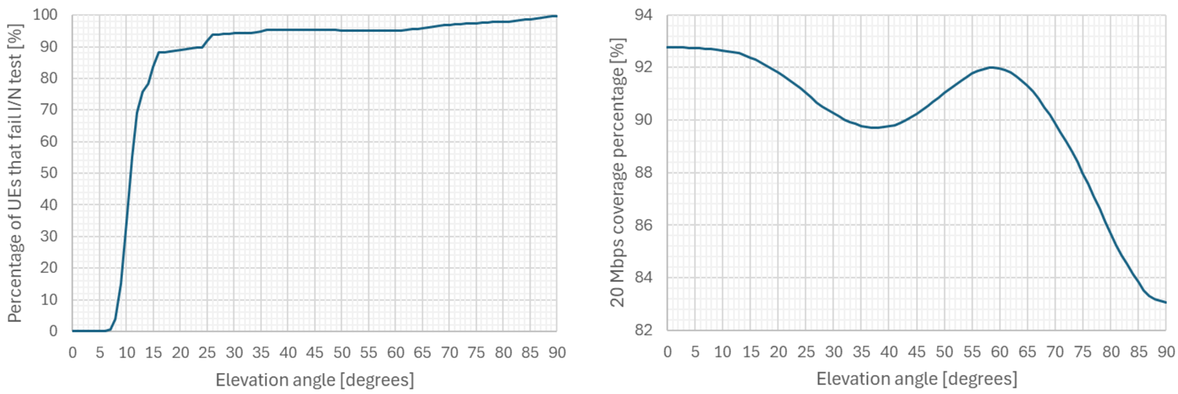
Table 5-8. Simulation parameters for low elevation angles in an urban environment according to 3GPP TR 38.811

Environment type	Reference elevation angle [°]	LoS standard deviation [dB]	NLoS standard deviation [dB]	Clutter loss (only for NLoS paths) [dB]
Urban	10°	4	6	34.3
Suburban/Rural	10°	1.79	8.93	19.52

The percentage of UEs that fail the I/N target increases rapidly for elevation angles greater than approximately 8° (Figure 5-12a), as the distance of the airborne platform reduces considerably (505 km at the horizon, at 0° elevation, vs. 130 km at 8°, which it translates to approximately 12 dB reduction on the propagation loss).

If we consider though the service requirements and allow for a level of performance degradation, the separation distances of the 20 Mbps service for 2%, 5% and 10% degradation are 46.4 km, 6.4 km, and 1.6 km respectively, which allows the airborne platform to operate much closer to the terrestrial network.

In this scenario, given the larger intersite distance (0.8 km), there were more cases than in the urban environment, where the UEs connected to the airborne platform. At 90° elevation angle, there were on average 8 users connected to the HIBS platform.



(a) **(b)**

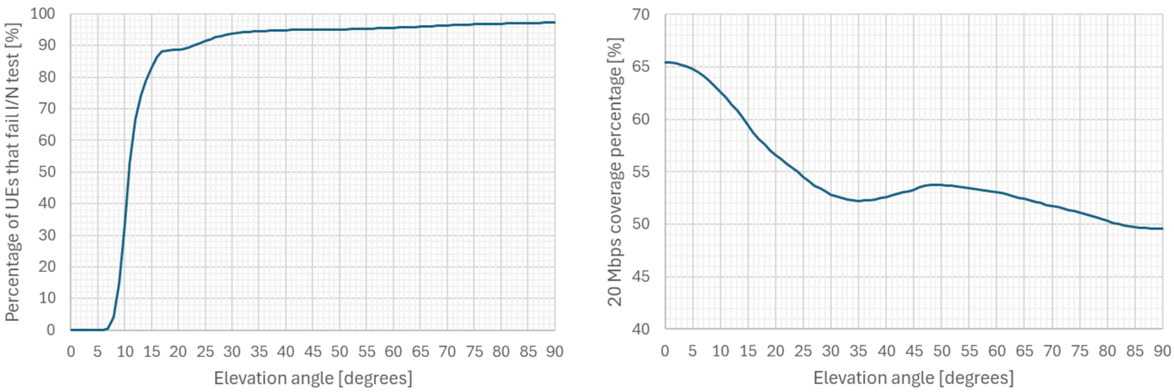
Figure 5-12. (a) The percentage of UEs that fail the I/N target and (b) the coverage percentage of a 20 Mbps service vs. the elevation angle of the HIBS platform in a suburban environment.

Rural environment

The rural scenario displays similar performance for the separation distance with respect to the I/N target, as in the suburban case. In the rural scenario this distance equals to 179.7 km (elevation angle of approximately 5.5°) (Figure 5-13a).

However, if we consider the service performance degradation, that distance decreases to 126.1 km, 78.9 km, and 47.2 km for 2%, 5%, and 10% degradation respectively from its maximum coverage (Figure 5-13b).

The overall coverage of the rural scenario is less than the urban and suburban environments due to the longer intersite distance (4 km), despite the higher transmit power (61 dBm vs 59 dBm for the urban and suburban scenarios).



(a) **(b)**

Figure 5-13. (a) The percentage of UEs that fail the I/N target and (b) the coverage percentage of a 20 Mbps service vs. the elevation angle of the HIBS platform in a rural environment.

5.2.4 Recommendations for the potential for more intensive sharing

In this technology pair, we have compared the separation distances between a HIBS and an IMT terrestrial network, based on the I/N target and on the performance of a 20 Mbps service.

Considering the service requirement, and an acceptable level of performance degradation, we can reduce the separation distance between the HIBS platform and the terrestrial network.

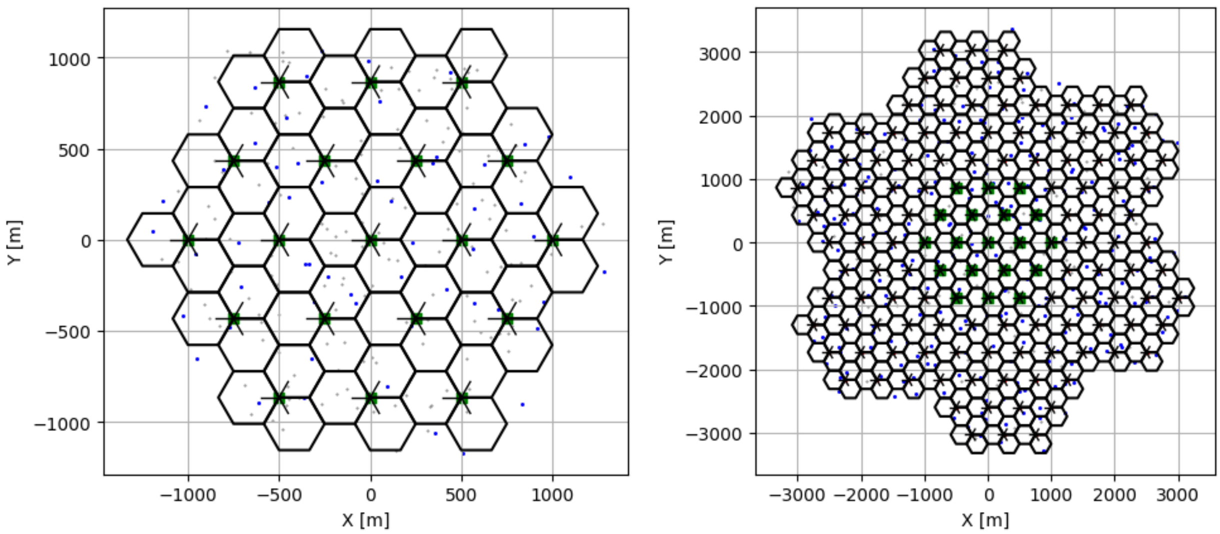
5.3 Mobile and fixed service in the upper 6 GHz band

The spectrum sharing between mobile and fixed service (FS) links in the upper 6 GHz band (6.425-7.125 GHz) is a challenging area and requires tens of kilometres separation according to the current calculations. In this section we assess this argument and how such sharing may become more efficient.

The 6 GHz band is used by several sectors, including MNOs and the financial sector, to deploy fixed links. According to Ofcom [23], most FS Links in this frequency band are utilised for mobile backhaul, programme-making and special events (PMSE), satellite services, public sectors, utilities, and financial services, such as high-frequency trading links. Approximately 500 links operate within this band, they are distributed across the UK and support various industries.

High-frequency trading links for financial services are primarily concentrated around London, while those used by the petrochemical sector are mostly located offshore. In contrast, links for mobile backhaul are widespread throughout the country, particularly in Scotland. Existing studies indicate that separation distances ranging from tens of kilometres (for instance, between 10 km and over 100 km) are likely needed between mobile base stations and fixed links. We model the mobile network as a cluster of 19 sites deployed in a hexagonal grid. Each has three cells/sectors, where the azimuthal directions are at [30^o, 150^o, 270^o]. Overall, there are 57 sectors (Figure 5-14a). The choice of the hexagonal grid is to comply with industry practices.

The inter-site distance between the sites in the graph depends on the scenario and it is a simulation parameter. When assessing the behaviour of a cellular network, it is important to remove any artefacts due to boundary conditions [24]. For that reason, we use a wrap-around technique that creates a toroidal area, where the central cluster is replicated 6 times around the central point (Figure 5-14b). When reporting results though, we only report for the ones that are related to the central cluster, the focus area.



(a) (b)

Figure 5-14. (a) A section of a mobile network consisted of 19 sites, deployed at a hexagonal grid, and (b) a cellular network, with the wrap-around technique, where the green squares represent the sites in focus.

In every cell, we deploy a number of users, from which we select a subset of those as being active. The number of active users within each cell is a simulation parameter.

Each cell is equipped with a 256-element antenna [16x8x2; 16 rows, 8 columns, 2 polarisations], where each antenna element radiates with 8 dB gain (Figure 5-15). The height of the cells depends on the environment, while the height of the user equipment is set to 1.5 m. If the cell generates more than one beam, the transmitted power is divided equally to each beam. To avoid high inter-cell, cross-beam interference, we assume that users (and their corresponding beams) are 15° or more apart, otherwise, the users share that beam and its resources, while the algorithm places the beam to point between the UEs, to ensure a good performance for both users (Figure 5-15c).

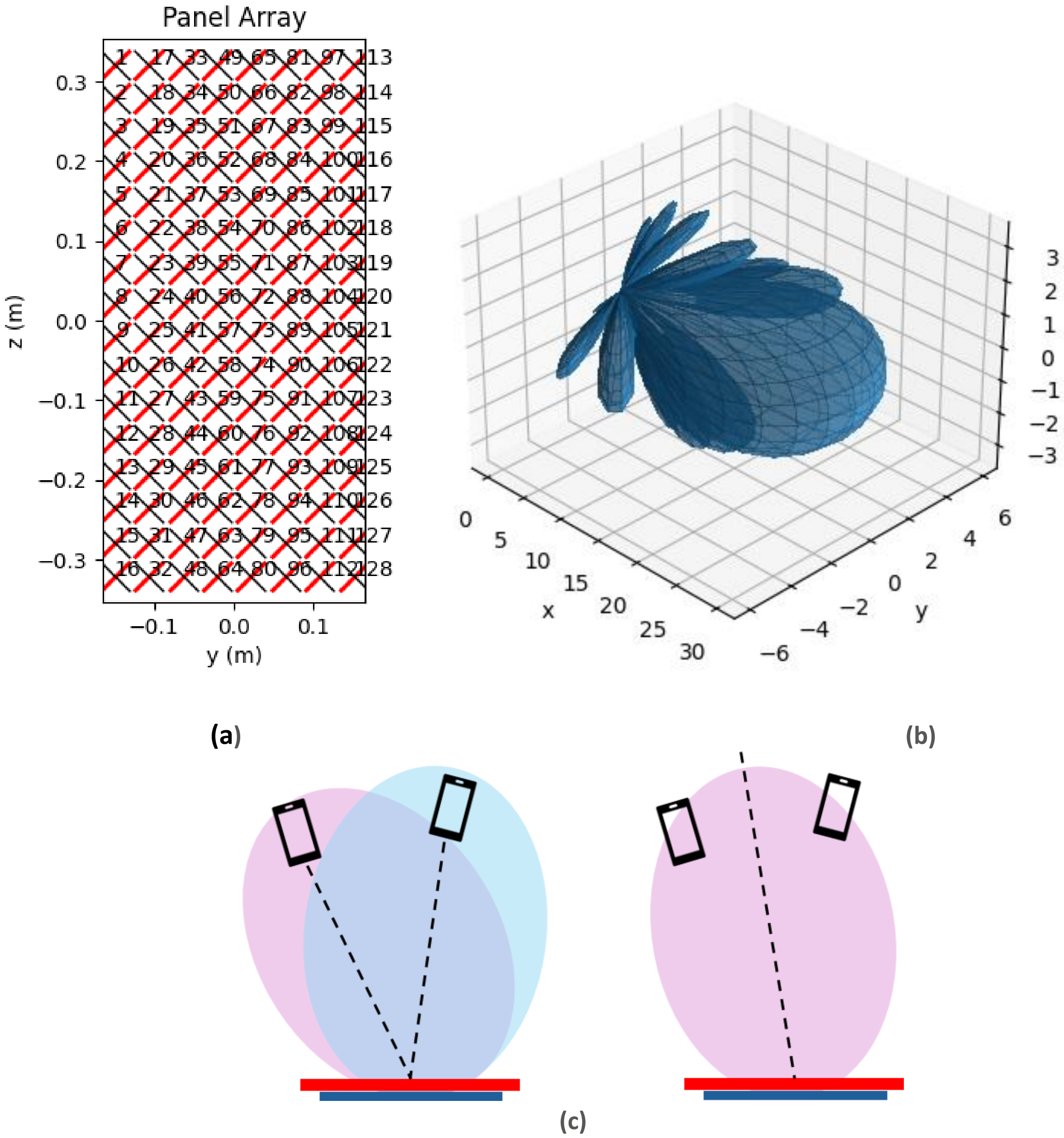


Figure 5-15. (a) A 256-element panel antenna, with 16 rows, 8 columns and 2 polarisations (cross-polarisation). The distance between the vertical and horizontal elements is λ/2. (b) The main beam lobe for the panel array at the antenna boresight. (c) UEs with small angular separation between them share a beam and consequently its resources. In this case, the interference is reduced and the power of the beam increases, as the base station transmits less beams.

We then place a FS linkend at a certain distance from the mobile network and we assess the interference levels. We assume that the FS link operates with 40 MHz bandwidth, as this is what the majority of the currently deployed FS links operate with in this band (Table 5-9) [25].

Table 5-9. The bandwidth and the number of links for FS operating between 6.425 and 7.125 GHz

Bandwidth [MHz]	Number of links	Percentage
20	74	4%
30	554	28%
40	1362	68%
60	20	1%

For every spatial separation between the focus area of the mobile network and the FS link, we run the calculations for 1,000 iterations. In each iteration, we set the azimuthal orientation of the FS linkend randomly in the [0^{o}, 360^{o}) space – to ensure that there are no random artifacts from the mobile network configuration (mainly the base station beams towards the UEs) – and we calculate the interference to the FS from the base stations in the focus area of the mobile network. We assume a flat terrain for this calculation [15]. We perform this for two FS linkend realisations, one linked pointing towards the centre of the mobile network, and one linkend pointing away from the mobile network.

We assume that the mobile network operates with a bandwidth of 40 MHz and that it is in the same channel as the fixed service link. Even though we assume that the mobile network operates in TDD mode, while the FS operates in FDD mode, we calculate the worst case, the maximum interference power, rather than the average over a frame.

We will repeat this process for different locality types.

5.3.1 Parameters

Below are the main simulation parameters that we use for this technology pair.

Table 5-10. Parameters and assumptions for the FS links in the upper 6 GHz.

	Fixed links
Frequency band	6.7 GHz
Bandwidth	40 MHz [26]
Duplex method	FDD [27]
Antenna type	Rec. ITU-R F.699-8
Antenna height	20 m [26]
Antenna gain	38 dBi [26]
Losses	2 dB
Noise figure	6.5 dB [26]

Table 5-11. Parameters and assumptions for terrestrial IMT network

	Base station	User equipment
Frequency band	6.7 GHz	
Bandwidth	40 MHz	
Percentage of UE outdoor	100 %	
Duplex method	TDD	
Directional resource split	75% [DL]	25% [UL]
Number of sites/users	19 (hexagonal grid)	3,000 (3 active per small cell)
Transmit power/EIRP [26]	76 dBm (80 dBm/100 MHz)	23 dBm [28]
Intersite distance [28]	Urban: 0.4 km Suburban: 0.8 km Rural: 4.0 km	N/A
Antenna type	MIMO [16x8x2]	Omni
Antenna height [28]	Urban: 20 m Suburban: 25 m Rural: 30 m	1.5 m
Antenna gain	8 dBi	-3 dBi [28][29]
Antenna downtilt [28][29]	Urban: 10° Suburban: 6° Rural: 3°	0°
Noise figure	7 dB	9 dB [29]
Propagation loss model	3GPP TR 38.901	
Environment type	Urban: Urban macrocell (UMa) Suburban: Urban macrocell (UMa) Rural: Rural macrocell (RMa)	

5.3.2 Model results and extensions

The results show that for the worst-case scenario, when the FS linkend points towards the mobile network, a large separation distance is required, ranging from 67.5 km for the urban environment to 174.2 km for the rural one. These results are with 95% confidence. The variability stems from the randomness in the pathloss calculations, but also more importantly from the randomness of the UE locations and their corresponding MIMO beams from the serving base stations.

For the case where the FS linkend points away from the mobile network, this distance can be greatly reduced, and the linkend can be placed almost to the edge of the mobile network. This is mainly due to the high front-to-back ratio of the antenna at the FS linkend.

In our analysis, we have assumed a flat terrain, however, at very long distances this assumption does not hold true, and we may therefore overestimate the propagation loss. Therefore, a more appropriate model is required, suited for such occurrences.

Table 5-12. The minimum distance between the FS linkend and the cellular network (in brackets is the distance from the centre of the cellular network)

Environment type	I/N separation distance [km] - [FS azimuth towards the IMT network]	I/N separation distance [km] - [FS azimuth away from the IMT network]
Urban	67.5 km (70 km)	0.46 km (2.75 km)
Suburban	69 km (74 km)	0.32 km (3.25 km)
Rural	174.2 km (198.4 km)	1.24 km (11.25 km)

Urban environment

In an urban environment, a FS linkend that points towards the network is required to be at distance of 67.5 km. This distance corresponds to the distance of the linkend to its closest base station in the network (the equivalent distance to the network centre is 70 km).

On the other hand, if the FS linkend points away from the network, then this distance reduces to approximately 0.46 km (2.75 km from network's central point). This distance corresponds almost to the edge of the mobile network, since in this scenario we have assumed that the intersite distance between the base stations is 400 m, and there are 19 sites, hexagonally placed in the focus area. We can place the FS linkend so close to the network in this case, due to the high front-to-back ratio of the antenna at the linkend (63 dB)

Suburban environment

Similar comments, as in the urban environment, are valid for the suburban environment. The separation distance between the mobile network and the FS linked is approximately 69 km (or 74 km from the network centre), while for the case where the FS linkend points away from the network, this distance reduces to approximately 0.32 km (3.25 km from the centre). Again, this distance is at the edge of the network, considering that the intersite distance for the suburban environment is 800 m.

Rural environment

We conducted the same analysis for a rural environment as we did for the suburban area.

5.3.3 Recommendations for the potential for more intensive sharing

The results indicate that in the worst-case scenario, when the FS linkend is oriented towards the mobile network, a significant separation distance between the IMT (International Mobile Telecommunications) and FS is necessary. This distance ranges from 67.5 km in urban environments to 174.2 km in rural areas. Conversely, when the FS link end points away from the mobile network, this separation distance can be greatly reduced, allowing the link end to be positioned almost at the edge of the mobile network. This reduction is primarily attributed to the high front-to-back ratio of the antenna at the FS link end. Further, based on our current analysis, we see an opportunity to enhance the effectiveness of sharing by utilising accurate propagation models.

6. Final remarks

This report provides the WP2 outcomes for the simulation and modelling activities in the Spectrum Sandbox project. It describes the high-level architecture and main components of the simulation tools and how we use these for each technology pair, both for the ones which are part of the testbeds, as well as their extension to additional technology pairs and types of environments. During our field trials in WP1, we tested two technology pairs in a sandbox environment. (1) Mobile and Wi-Fi in the upper 6 GHz band and (2) independently operated private networks in the upper n77 band.

Firstly, we explored how we could apply some of the principles and learnings from WP1 to generalise the findings so that the spectrum-sharing principles demonstrated in WP1 could be expanded upon. Our analysis of the channel models confirms that using a deterministic channel model, such as a ray-tracing algorithm, provides much better prediction accuracy. However, the use of deterministic channel models cannot be generalised to all deterministic models or environments. Further testing of this hypothesis is necessary across various locations and environments (urban, suburban, rural) and including more prediction models to draw stronger conclusions. Furthermore, a multi-model approach may be necessary in the licensing process to better understand the impact of new networks on existing ones. A model mapping SINR values to spectral efficiency has been developed and applied in the assessment of WP2.

During our field trials in WP1, we tested two technology pairs in a sandbox environment. (1) Mobile and Wi-Fi in the upper 6 GHz band and (2) independently operated private networks in the upper n77 band.

In our assessment of sharing between mobile services and Wi-Fi in the upper 6 GHz bands through cross-technology signalling. This approach allows for detecting mobile services in Wi-Fi areas and activating mitigation measures to reduce interference. Successful implementation of XTS to enable sharing between IMT and Wi-Fi depends on a well-defined regulatory framework and standards that address technical requirements and conformance testing. Without proper standardisation, the sharing framework may remain theoretical, and early market entry of Wi-Fi could deter investment from the IMT sector. Additionally, an enforcement framework is necessary to ensure that devices cannot be modified aftermarket to alter their behaviour, which would instil confidence in MNOs to invest.

Key findings from our analysis of independently operated private networks in the n77 band indicated that reducing the geographical separation between networks is possible without compromising service performance. Allowing a certain level of performance degradation can further decrease the separation distance between networks, thus increasing spectrum intensity. Accurate modelling of network locations and configurations is essential for understanding the performance and impacts of adjacent networks. Precise prediction models provide less restrictive licence conditions, allowing licensees to deploy networks close to each other than is possible today. Densifying network deployments are particularly helpful in urban areas where techno-economics of networks are challenging.

We also explored how we could apply key principles and learnings from WP1 to additional technology pairs in other frequency bands. Many past coexistence studies have been performed on these technology pairs for regulatory purposes; therefore, we aimed not to conduct further exhaustive studies. Instead, we limited our assessment to applying learnings from the sandbox experiments to gain further insights. We selected three additional technology pairs for this assessment:

3. Mobile and satellite – Direct-to-device satellite in the 2.6 GHz band
4. Mobile and airborne non-terrestrial networks (NTN)
5. Mobile and fixed links in the upper 6 GHz band

We have obtained two key learnings from WP1: improvements in the channel model and mapping of Signal-to-Interference-plus-Noise Ratio (SINR) to throughput. Our analysis of the above technology pairs concluded that the generalised channel models closely align with the measurements conducted in WP1. Consequently, we utilise the generalised channel model for all mobile technology assessments in these additional technology pairs. Additionally, we employed the SINR-to-throughput mapping model for all mobile deployments.

Based on our current analysis, we see an opportunity to enhance the effectiveness of sharing by utilising accurate propagation models, which vary in precision. By considering multiple models, we can achieve more precise predictions.

Appendix A Acronyms

Abbreviation	Definition
3GPP	3rd Generation Partnership Project
AAS	Active Antenna System
AP	Access Point
AOS	Acquisition of the Satellite
BS	Base station
CDF	Cumulative Distribution Function
CL	Coupling Loss
CEPT	European Conference of Postal and Telecommunications Administrations
CW	Continuous Wave
D2D	Direct to Device
DSIT	Department for Science, Innovation and Technology
EIRP	Effective Isotropic Radiated Power
ECC	Electronic Communications Committee
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FS	Fixed Service
FSPL	Free Space Path Loss Calculator
HIBS	High- altitude platform station as International Mobile Telecommunications base station
IMT	International Mobile Telecommunications
ISD	Inter-Site Distance
ITU	International Telecommunication Union
KPI	Key performance indicator
LEO	Low earth orbit
LoS	Line of Sight
MCS	Modulation coding scheme
MNO	Mobile Network Operators

Abbreviation	Definition
MP	Medium Power
NLOS	Non Line of Sight
NTN	Non-terrestrial network
PFD	Power Flux Density
PMSE	Programme Making and Special Events
QoE	Quakity of Enperience
RHCP	Right-Hand Circular Polarisation
RLAN	Radio Local Area Network
RSSI	Received Signal Strength Indicator
S(I)NR	Signal-to(-Interference-and)-Noise-Ratio
SAL	Shared Access Licence
SCS	Supplemental Coverage From Space
SE	Spectral Efficiency
SSB	Synchronization Signal Block
TDD	Time Division Duplex
RE	Resource Element
RLAN	Radio Local Area Network
UE	User equipment
WAS	Wireless Access Systems
WP	Work Package
XTS	Cross Technology Signalling

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