Spectrum Sandbox Report on Propagation Measurements, Dissemination and Policy

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1. Introduction

An overview of the project background is briefly described followed by the upgrade of the Durham channel sounder and propagation measurements conducted to support the sandbox in work packages WP1 and WP2 with a summary of the results.

The report then outlines the dissemination activities both in conferences, workshops and meetings and plans for further dissemination and contributions to international standards.

1.1 Project background

As the spectrum in the lower frequency bands became highly congested, the mm wave and sub-THz bands have attracted a great deal of interest for potential high data rate low latency applications. Although these frequency bands have a great deal of contiguous unallocated spectrum, the propagation characteristics in these high frequency bands such as scattering due to precipitation, high loss due to diffraction and obstructions limit their deployment for short range scenarios such as for building-to-building fixed links, or for short range applications such as lamppost to user. Large area coverage is therefore, better served by lower frequency bands such as the upper 6 GHz band (6.425-7.125 GHz). To enable the effective use of this band by different services, Ofcom set out its plans for spectrum sharing between nine different pairs which also included private networks in the N77 band (3.3-4.2 GHz) to be investigated in three different sandboxes in three work packages:

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

The Durham Sandbox in collaboration with four industrial partners: TRL, Telet, Ranplan Wireless and London Economics investigated five pairs with the first four pairs in the upper 6 GHz band:

- Wi-Fi and mobile
- Fixed links and mobile
- UWB and mobile
- Receive-only users (scientific applications) and mobile

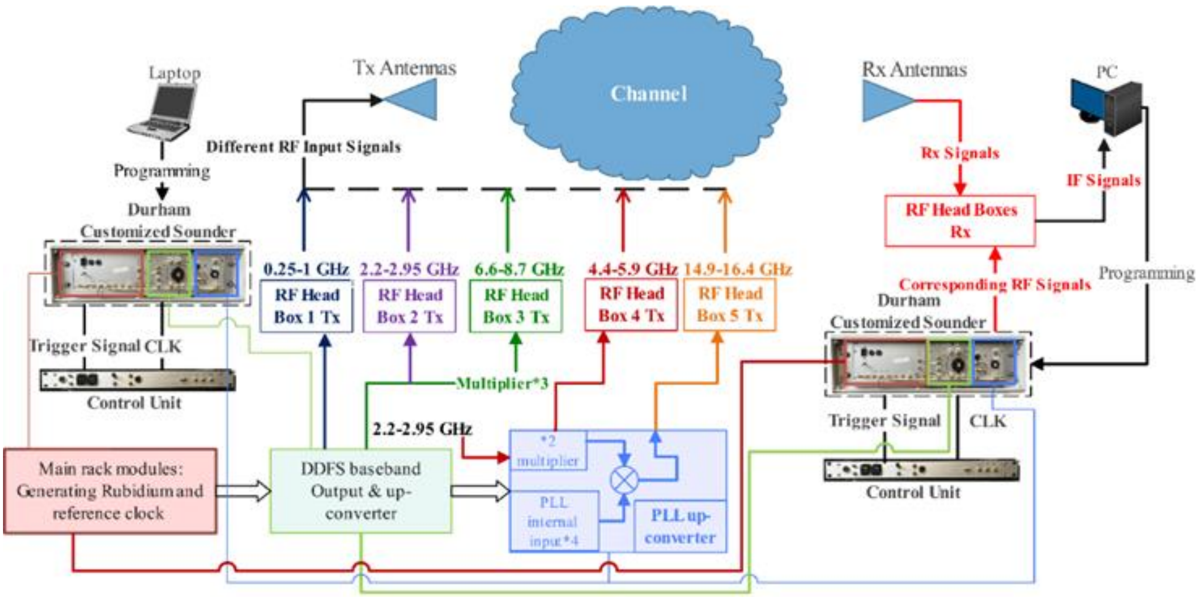
Independently operated private networks (IOPN) in the N77 band

To evaluate the potential of sharing the spectrum, the interference between pairs was investigated through simulation of the five pairs and where necessary exclusion distances were identified such as for mobile and astronomy (scientific applications), mobile and UWB radar, and mobile and fixed links. Wi-Fi and mobile spectrum sharing was investigated with the potential of spatial separation such as indoor for Wi-Fi and mobile for outdoor particularly in the dense urban environments where high rise buildings and penetration loss into modern buildings limits the indoor coverage of mobile radio networks.

2. Propagation measurements to support the sandbox

To facilitate the simulation in WP2 and the validation in the testbed in WP1, and since commercially available RF heads are limited to the 5 GHz, the custom designed multiband Durham University channel sounder was upgraded to cover the band 6.6-8.7 GHz using frequency multipliers to interface with the output at 2.2-2.9 GHz as illustrated in Figure 1. The IF output in the final stage which is programmable to cover the band from 12.5-18 GHz with 1.5 GHz band feeds into multiple RF heads in various frequency bands from 24-29 GHz, 39-42 GHz, V band (50-75 GHz), E band (60-90 GHz), and two sub-THz RF heads: 110-170 GHz and 230-320 GHz.

The sounder which can be operated either from the mains or batteries is mounted on a custom designed trolley as shown in Figure 2 to facilitate indoor, outdoor below roof top and above roof top, and outdoor to indoor measurements both on site and off site. The sounder has been used in numerous propagation studies and the results were submitted to the International Telecommunications Union Study Group 3 and incorporated in the generation of different propagation models in ITU-R recommendations including: ITU-R P. 1411 for outdoor scenarios, ITU-R P. 1238 for indoor scenarios, the development of the building entry loss recommendation ITU-R P, 2109 and ITU-R P. 530 for the impact of precipitation on mm wave links. Since the current recommendation ITU-R P. 1411 non-line of sight model for below rooftop for the Urban low-rise / Suburban environment is currently limited to 10-73 GHz, outdoor measurements across multiple frequency bands were performed as given in Table 1 with the upper 6 GHz band measurements being used to calibrate the ray tracing tool in WP2 and the measurements in the 5 GHz band to provide the necessary information regarding the difference between the RF heads in the 5 GHz band used in the testbed of WP1 and the upper 6 GHz band. In the measurement, the transmitter was set up at 2.4 m and the receiver at 1.6 m and omni-directional antennas were used at both ends of the link as in the layout of Figure 3. The data were processed to estimate the path loss across each frequency band and across all the five bands. The results of the model fitting across the 5 GHz and upper 6 GHz band bands are illustrated in Figure 4 for both line of sight (LoS) and non-line of sight (NLoS) cases with Table 2 summarising the results where it can be seen that the difference between the measured frequencies and the operating frequencies is ~1 dB and the difference between the measured path loss and the free space path loss is <0.6 dB.



(a)

(b) (c)

Figure 1. (a) Durham University multiple band Channel Sounder with multiple RF heads, (b) mm Wave dual transmitter/receiver RF head, (c) the RF head to cover the upper 6 GHz band

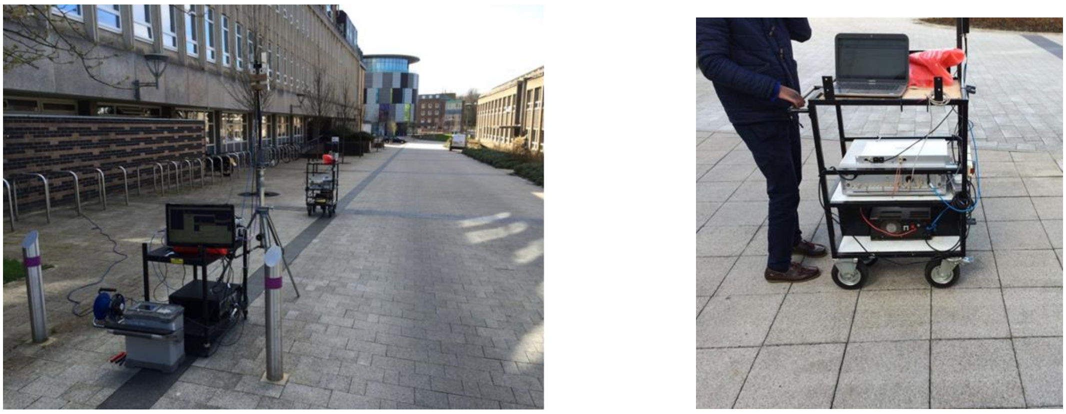
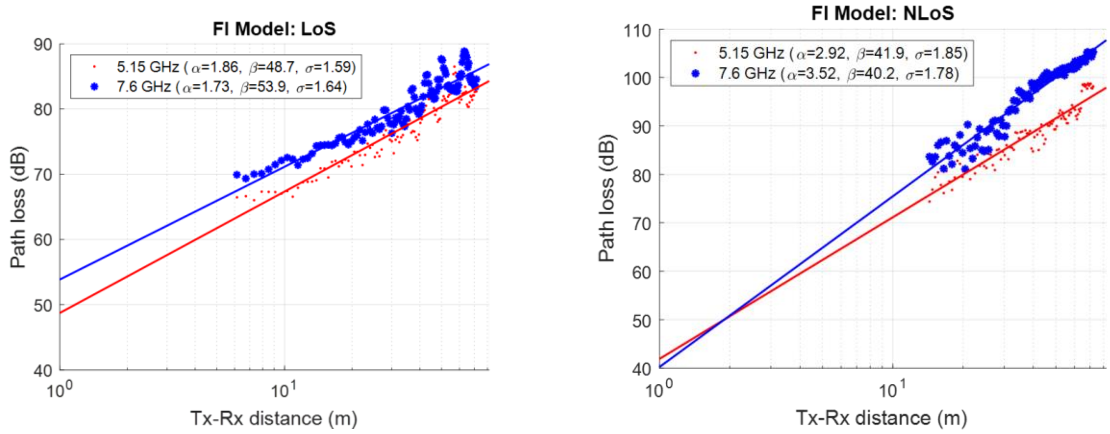


Figure 2: Typical measurement scenario in a suburban environment

System Parameters					
Measured Frequency (GHz)	0.25-1	2.2-2.95	4.4-5.9	6.6-8.7	14.9-16.4
Processed Frequency (GHz)	0.3-0.6	2.3-2.8	4.5-5	6.8-7.3	15-15.5
Center Frequency (GHz)	0.45	2.55	4.75	7.05	15.25
Processing Bandwidth (MHz)	300	500			

Table 1: Sounder parameters for the outdoor measurements across five frequency bands

Figure 3. Measurements scenario for both line of sight (LoS) and non-line of sight (NLoS)



(a) (b)

Figure 4. Path loss at 5.15 GHz and 7.6 GHz, for (a) LoS, (b) NLoS

Frequency	Free Space Path Loss at 21 m
7.6 GHz	76.52 dB (75.94 dB measured)
6.775 GHz	**75.52 dB**
5.8 GHz	**74.17 dB**
5.2 GHz	73.22 dB (73.43 dB measured)

Table 2. Summary of path loss results

The measurements were provided to WP2 to calibrate the simulation tool for evaluating the potential of spectrum sharing for the four pairs in the upper 6 GHz band.

The other set of measurements was conducted to support the penetration loss of typical walls as illustrated in Figure 4. The figure shows that the penetration loss of an indoor wall can very between 2.8 to 16.9 dB with an indoor brick wall exhibiting 15 dB loss. Outdoor to indoor penetration loss of a double-glazed glass wall varied between 28 to 36 dB depending on the angle of incidence of the wave.

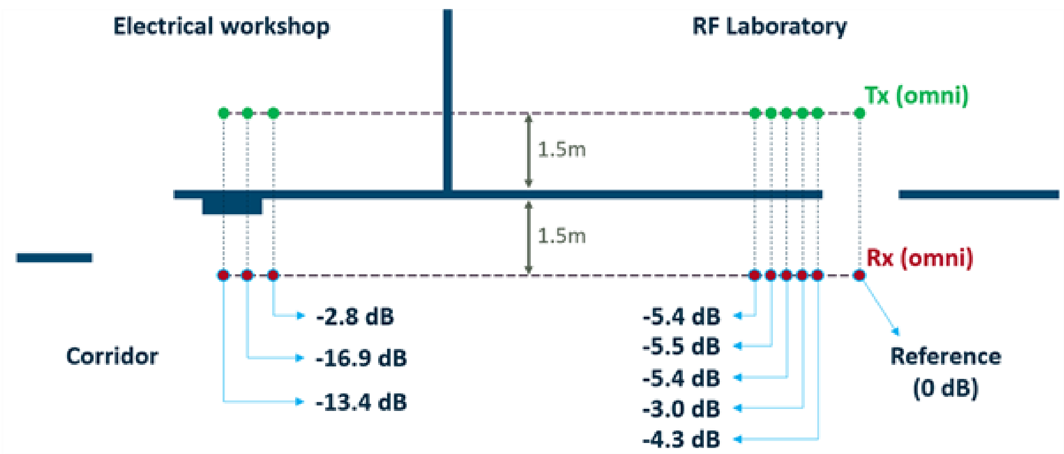


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Figure 4. Penetration loss through indoor wall

Further measurements were performed in modern building with glass from outdoor to indoor as illustrated in Figure 5. Measurements were taken outside and inside the building and the loss was estimated for the difference between outdoor and indoor signal level. The building entry loss was estimated from 23 measurements: (34.25 35.64 33.36 32.26 28.44 26.78 30.63 35.2 38.77 39.81 37.13, 36.43) giving a median value of 34.73 dB and a standard deviation of 3.98 dB.

Figure 5 Scenario of measured modern building entry loss

3. Dissemination activity

An overview of the sandbox and results of the propagation measurements and simulations in WP2 have been presented in the following meetings:

1. World Wireless Research Forum, London, September 2024
2. London Economics presented work in progress on WP3, alongside the other Sandboxes, at a Sandbox Innovation session on WP3, London, 28 August 2024
3. The Sandbox presented work in progress and preliminary results at a UK Spectrum Policy Forum Workshop, alongside the other Sandboxes, London, 18 January 2025
4. London Economics presented preliminary results at an industry stakeholder workshop, online, 7 March 2025
5. The Sandbox presented a keynote at the national URSI workshop held in Durham on the 13th of March 2025
6. European COST Action INTERACT 10th Management Committee meeting, 27th -30th January 2025. Technical document can be found in the annex.

The following papers have been accepted/submitted to international conferences:

1. Paper **accepted** in EUCAP 2025 (March 30 - April 4, 2025), Stockholm, Sweden.
2. Durham/Ranplan submitted **two** joint papers to the International Union of Radio Science, URSI, Conference to be held in Sydney August 2025. One paper on the Mobile/Astronomy Scenario and a second invited paper on the UWB/Mobile Scenario.
3. Invited to attend the DySpan panel discussion in May 2025. A poster has been submitted.
4. An invitation has been received to present the Sandbox outcome at the Defence manufactures' Spectrum Forum in September 2025.

Contribution to International Standards: Technical documents will be submitted to the International Telecommunications Union, Study Group 3 for the May/June 2025 meeting to update the propagation models in ITU-R P.1411-12 for non-line of sight scenarios to cover the frequency band from 0.45 GHz (currently it covers 10-73 GHz). In preparation for the SG3 meeting, the data were submitted to the Correspondence Group CG-3K-6 to update the model in collaboration with other administrations.

4. Engagement of Young Researchers

As per the scope of the sandbox young researchers participated in the measurements and data analysis which included:

- The participation of MSc students in field trials
- PhD students training in calibration and set up of RF heads in the upper 6 GHz band
- PDRAs participation in measurements, data processing and modelling
- The Sandbox enabled the appointment of young researchers and training in spectrum sharing aspects

5. Policy Recommendations

Following the simulations undertaken in work package 2, we would like to highlight the below policy considerations for Ofcom

1. Distance restrictions for Astronomy

Distance will be based on the site, but the highest protection for rural areas would be for mobile operators to site their base stations 91km away (Deliverable 2.4 , section 3.4)

2. Distance restrictions for UWB Radar

150m protection area (Deliverable 2.4, section 3.3.2.2)

3. Fixed Link

It is suggested that Ofcom considers allocating an alternative spectrum when the current license expires.

4. **Regulation of transmitted power** for Mobile to enable spectrum sharing of the Indoor/Outdoor scenario with Mobile and WiFi.

5. **Open consultation** regarding the proposed solutions by the Sandboxes, for example the Outdoor/Indoor scenario proposed by this Sandbox.

CA20120 TD(25)10033
Dublin, Ireland
January, 27-30, 2025

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Channel Measurement and Modelling in a suburban environment across five bands up to 15.5 GHz

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Channel Measurement and Modelling in a suburban environment across five bands up to 15.5 GHz

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Abstract

With the increasing shortage of current spectrum resources, the next generation of mobile communications demands access to new frequency bands. At the International Telecommunication Union (ITU) World Radio Conference 2023 (WRC-23), the 7.125–8.4 GHz and 14.8–15.35 GHz bands were identified as potential candidates for next-generation mobile communication. To lay the groundwork for system design in these new bands, extensive channel measurements are essential to explore and validate their characteristics. In this technical document, outdoor wideband channel measurements in a suburban environment were conducted across five bands in the frequency range 0.3 to 15.5 GHz. The channel sounding system and measurement methodologies are described followed by the estimation of path loss which was fitted by the commonly used single frequency and multiple frequency path loss models.

1. Introduction

Recently, several international communication organizations, such as the International Telecommunication Union (ITU), the U.S. National Telecommunications and Information Administration (NTIA) and the Federal Communications Commission (FCC), have shown significant interest in the 4–8 GHz FR1(C) and 7–24 GHz FR3 frequency bands, which are still available [1]. The lower mid-band of FR1(C) frequencies, while it may need to be shared with existing applications (e.g., satellite services and radio astronomy), still holds significant potential for mobile communication. This band could be deployed without major modifications to current cellular network architectures or overly complex upgrades to existing communication equipment and testing systems. The 7–24 GHz FR3 band offers relatively larger bandwidth compared to the saturated below 6 GHz spectrum while providing better coverage than the highly attenuated THz waves. This enables a balance between capacity and coverage. The ITU WRC-23 conference identified the 7.125–8.4 GHz and the 14.8–15.35 GHz bands as new spectrum bands for mobile communications [1]. In addition, the UHF band, in the 470-694 MHz frequency range, which is currently used for Digital Terrestrial Television (DTT), and considering the decisions at WRC-23, to allocate it to mobile on a secondary basis, and the expiration of DTT broadcast licences in 2034, measurements were conducted to cover five frequency bands including the UHF band, which can support long-distance transmission, making it a viable supplement to address signal blind spots caused by the limited coverage of high-frequency band signals. Currently the ITU-R P. 1411-12 recommendation has path loss models for several outdoor environments classified as below roof top and above rooftop. The non line of sight (NLoS) model in urban low rise/suburban environments covers the frequency range of 10-73 GHz. To extend the frequency range to the lower frequency band, measurements were performed both in LoS and NLoS in suburban environment to complement the data base and update the model.

2. Measurement sounder and environment

The measurements were conducted with Durham University multiple band sounder which has been upgraded with new RF heads to cover the frequency range in the upper 6 GHz band. The measurements were conducted with omnidirectional antennas at the transmitter and receiver where the transmit antenna was set up at 2.4 m above ground and the receive antenna at 1.6 m. Table 1 gives the frequency bands of the measurements, the bandwidth of the measurements and the frequency range that was processed for the estimation of the channel parameters. The data were collected over 1 second per location with a sampling rate of 40 MHz. Figure 1 illustrates the measurement environment for both LoS and NLoS location of the transmitter.

System Parameters					
Measured Frequency (GHz)	0.25-1	2.2-2.95	4.4-5.9	6.6-8.7	14.9-16.4
Processed Frequency (GHz)	0.3-0.6	2.3-2.8	4.5-5	6.8-7.3	15-15.5
Center Frequency (GHz)	0.45	2.55	4.75	7.05	15.25
Processing Bandwidth (MHz)	300	500			

Table 1. Measurement parameters

Figure 1. Measurement environment

3. Path loss channel models

The path loss estimation can be either for a single frequency where there are two commonly used models: the Floating-Intercept (FI) model and the CI free-space reference-distance model. The main difference between the CI and FI models is that the CI model uses the free space path loss (FSPL) at a 1-meter reference distance as a parameter, while the floating intercept parameter in the FI model is obtained through data fitting. Therefore, the parameter of the CI model has a physical correlation with frequency, while the parameter of the FI model is more flexible, providing a more precise but non-transferable fit. The ITU models both indoor and outdoor have now adopted the ABG model, which is a multiple frequency model, where the same set of parameters are used which provides a compact model as given in equation 1

$$\mathrm{PL}_{ABG}(f, d)[\mathrm{dB}] = 10\alpha \log_{10}\left(\frac{d}{d_0}\right) + 10\gamma \log_{10}\left(\frac{f}{1\mathrm{GHz}}\right) + \beta \qquad (1)$$

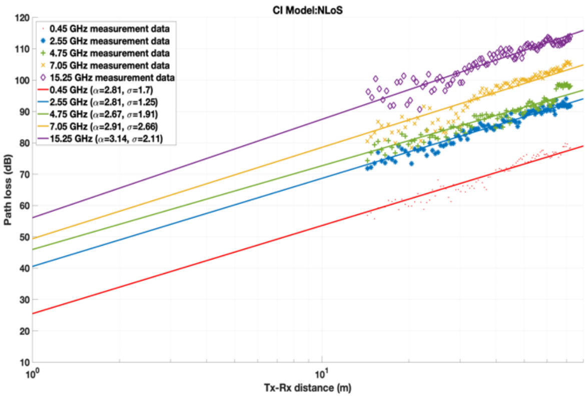
with an additive zero mean Gaussian random variable $N(0, \sigma)$ with a standard deviation σ (dB),

where α and γ are coefficients representing the impact of distance and frequency on path loss, respectively, while β is an offset parameter for path loss fitting optimization. The variable f denotes the frequency in GHz, and d_0 is the reference distance which is set to 1 m. The CI model and the FI models only provide one parameter as a function of distance as given in equations 2 and 3.

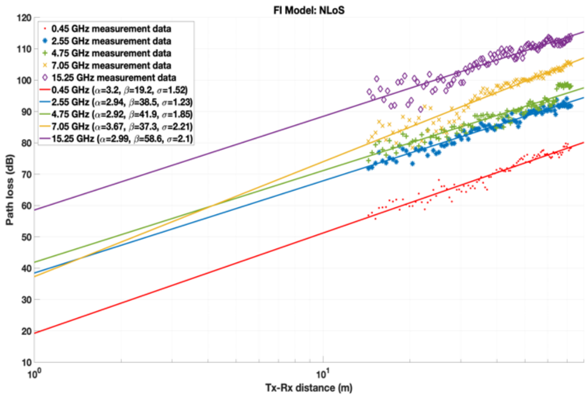
$$PL_{CI}(d) = FSPL(d_0)[dB] + 10n \log_{10}\left(\frac{d}{d_0}\right) \qquad (2)$$

$$PL_{FI}(d)[dB] = \alpha + 10\beta \log_{10}(d) \tag{3}$$

where n and β are the distance parameters and in the CI and FI models respectively and α is the offset fitting optimization. Figure 2 shows the fitting for the three models across the five measured bands for the NLoS case with the results summarised in Table 2 for both LoS and NLoS.



(a)



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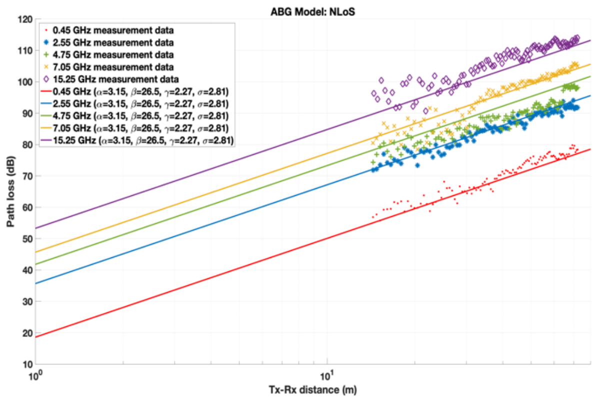

(c)

Figure 2. Path loss fitting for (a) CI model, (b) FI model and (c) the ABG model

Freq. (GHz)	(CI, $d_0 = 1m$)		FI			ABG				Dist. (m)
	α	σ (dB)	α	β (dB)	σ (dB)	α	β (dB)	γ	σ (dB)	
0.45	2 (2.81)	2.06 (1.7)	1.38 (3.2)	35.3 (19.2)	1.17 (1.52)					
2.55	2.04 (2.81)	1.9 (1.25)	1.55 (2.94)	48.3 (38.5)	1.34 (1.23)					
4.75	2.04 (2.67)	1.66 (1.91)	1.86 (2.92)	48.7 (41.9)	1.59 (1.85)	1.64 (3.15)	38.3 (26.5)	2.04 (2.27)	1.77 (2.81)	6-71.4 (14.4-72.2)
7.05	1.99 (2.91)	2.19 (2.66)	1.71 (3.67)	53.7 (37.3)	2.06 (2.21)					
15.25	2.09 (3.14)	2.18 (2.11)	1.71 (2.99)	62.1 (58.6)	1.92 (2.1)					

Table 2. Path loss model coefficients for the CI, FI and ABG models. Values in backets are for the NLoS case

Comparing the results for the LoS case with the current model in ITU-R 1411-12 for the urban high rise, urban low rise and suburban with parameters 2.12, 29.2, 2.11 and 5.06 covering the frequency range of 0.8 to 82 GHz and distances from 5 to 660 m a significant difference in the standard deviation is noticed which is due to the extended frequency range in the model adopted in the recommendation with respect to the current measurements and the model covers different environments and a significantly longer distance. In addition, the model in the recommendation is a compilation of data sets from different administrations which include Japan and Korea. For the NLoS scenario of the suburban/low rise urban below-roof-top cases, the ITU model starts at 10 GHz and the current measurements would enable its extension to start at 0.45 GHz.

4. Conclusion

Measurements in five frequency bands from 0.45 to 15 GHz were conducted to extend the frequency range of the ITU model for below roof top NLoS suburban/low rise urban to start at 0.45 GHz which currently starts at 10 GHz. This is particularly important to cover the frequency bands identified in WRC2023 and in the UHF bands which are currently used for digital TV broadcasting with the TV licence expected to expire in 2034. The measurements will be combined with the data in the ITU model to update the frequency range in Table 4 of the ITU-R P. 1411 recommendation.

Acknowledgement

The sounder at Durham University was developed under EPSRC grant PATRICIAN, EP/I00923X/1 and updated above 100 GHz under EPSRC grant TRACCS EP/W027151/1. The upper 6.6-8.7 GHz band was updated under DSIT funding of the Spectrum Sharing Sandbox led by Durham University.

References

[1] D. Shakya *et al.*, "Comprehensive FR1(C) and FR3 lower and upper mid-band propagation and material penetration loss measurements and channel models in indoor environment for 5G and 6G," *IEEE Open J. Commun. Soc.*, vol. 5, pp. 5192-5218, Jul. 2024.

[2] ITU-R P.1411-12 Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz .

FR3 Radio Propagation Channel Measurements and Modelling in Outdoor Environment for 5G and 6G Wireless Networks

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***Abstract*—Propagation channel measurements in Line-of-sight (LoS) and None-Line-of-Sight (NLoS) scenarios were conducted at 7.6 GHz and 13.6 GHz in the FR3 frequency band in a suburban outdoor environment at Durham University. The measurements employed omnidirectional antennas at the transmitter and receiver to evaluate multipath components and characterize the channel properties of these recently allocated frequency bands for International Mobile Telecommunications (IMT). The analysis covered several channel parameters, including the Power Delay Profile (PDP), Root-Mean-Square (RMS) delay spread, and the Rician K-Factor. Additionally, the path loss coefficient was estimated using both the Close-In (CI) and the Floating-Intercept (FI) models.**

***Index Terms*— propagation channel measurements, FR3, CI and FI path loss models, K-Factor, channel chracteristics, path loss.**

INTRODUCTION

In 2019, the World Radiocommunication Conference (WRC) identified the 24.5-71 GHz Frequency bands as an additional potential bandwidth for the development of the fifth generation (5G) communication systems. To identify the most suitable frequency for specific applications, extensive propagation channel measurements are required across different environments and scenarios. Since most of the time is spent indoors [1], numerous propagation channel measurements were conducted in indoor scenarios, especially in offices [2], industrial settings [3] and conference rooms [4]. The interest in the mm wave band led to research being mainly focused on several bands such as the Ka band (26.5-40 GHz) [5]; E band (60 -90 GHz) [6], [7]; D band (110-170 GHz) [8] and J band (220-325 GHz) [9]. However, in the World Radiocommunication Conference 2023 (WRC-23), several key frequency bands were identified to support the development and deployment of next-generation communication systems [10]. These include the 3.3–3.4 GHz, 3.6–3.8 GHz, 4.8–4.99 GHz, 6.425–7.125 GHz, 7-8.5 GHz and 14.8-15.35 GHz bands, which led to a new round of channel measurements to characterize the radio channel in these frequency bands. Currently, most of the reported studies on these bands are focusing on Outdoor-to-Indoor (O2I) scenarios [11], [12], rather than the outdoor environments only. In a recent study, Shakya et.al [13] presented a comprehensive study in general indoor environments at 6.75 GHz and 16.95 GHz. In [5], wideband measurements ranging from 2 to 28 GHz in a parking lot environment are reported, observing that the presence of cars had a minimal impact on the path loss across all frequencies. In this paper, we present the results of Outdoor Street-Canyon channel measurements conducted below the roof top in a suburban environment at 7.6 GHz and 13.6 GHz. The collected data were analyzed to estimate PDP, RMS delay spread, Rician K-Factor and the path loss coefficients based on the CI model and FI model.

The paper is organized as follows. Section II describes the channel parameters and models. Section III illustrates the measurement procedures and scenarios. Section IV presents the measurement results and analysis. Conclusions are drawn in Section V.

CHANNEL PARAMETERS AND MODELS

Root Mean Square (RMS) delay spread

RMS delay spread (τ_{RMS}) is a commonly used statistical measure of the dispersion of the time delays in a multipath channel estimated using Equations (1) and (2)

$$\overline{\tau^2} = \frac{\sum_k P_h(\tau_k)\,({\tau_k}^2)}{\sum_k P_h(\tau_k)} \tag{1}$$

$$\tau_{RMS} = \sqrt{\overline{\tau^2} - (\bar{\tau})^2} \tag{2}$$

where $\overline{\tau^2}$ is the second central moment of the PDP. $P_h(\tau_k)$ is the received power of the multipath component at time delay (τ_k) , $\bar{\tau}$ is the mean excess delay, which can be calculated using Equation (3)

$$\bar{\tau} = \frac{\sum_k P_h(\tau_k)(\tau_k)}{\sum_k P_h(\tau_k)} \tag{3}$$

Rician K-Factor

The Rician-K-factor describes the ratio between the signal with dominant power and the local mean power of the multipath components which can be estimated from small scale measurements at a particular frequency using the method of moments. For a stationary measurement the K factor can be estimated from the transfer function using equations (4)-(8) [14] where $|H_i|$ is the magnitude of the transfer function at frequency bin *i*

$$m_2 = \frac{1}{n}\sum_{i=1}^{n} |H_i|^2 \quad (4)$$

$$m_4 = \frac{1}{n}\sum_{i=1}^{n} |H_i|^4 \quad (5)$$

$$s = \sqrt[4]{2m_2^2 - m_4} \quad (6)$$

$$\sigma^2 = \frac{m_2 - s^2}{2} \quad (7)$$

$$K_{Factor} = \frac{s^2}{2\sigma^2} \quad (8)$$

where m_2 and m_4 represent the total power of the second and fourth moment in the signal, s denotes the strongest component, σ^2 represents the **multipath components** of the signal, capturing the fluctuations and variability caused by reflections and scattering.

Close-In model and Floating-Intercept model

Several path loss models are commonly used, including the Close In (CI) model and the Floating Intercept (FI) model estimated as in Equations (9)-(10) [6]

$$L_{CI}(d) = 10\log_{10}\left(\frac{4\pi f d_0}{c}\right)^2 + 10n\log_{10}\left(\frac{d}{d_0}\right) \text{ dB} \quad (9)$$

$$L_{FI}(d) = \alpha + 10\beta\log_{10}(d) \text{ dB} \quad (10)$$

with an additive zero mean Gaussian random variable $N(0, \sigma)$ with a standard deviation σ (dB) where d is the 3 dimensional distance between the transmitter and receiver. In Equation (9) d_0 represents the reference distance of 1 m, c denotes the speed of light, f is the operating frequency, and n is the path loss exponent. In Equation (10) α and β represent the Floating intercept parameters.

CHANNEL MEASUREMENT SETUPS

Channel Measurement System

The measurements were performed using the custom-designed multiband frequency modulated continuous wave (FMCW) channel sounder developed at Durham University. For the current measurements the sounder was upgraded using a time 3 frequency multiplier from the 2.2-2.9 GHz IF for the frequency range from 6.6 to 8.7 GHz to cover the frequency range in the upper 6G identified in WRC 23. Table I presents the channel sounder parameters used in the measurements which were conducted in a street-canyon scenario for both the LoS and NLoS cases. The Tx is set up on a Tripod while the Rx is mounted on a movable trolley to simulate a wireless access point under the roof top to a mobile user scenario. A total of 110 Rx locations were recorded for the LoS scenario, and 104 Rx locations were recorded for the NLoS scenario, for both frequency bands over a distance range from 6 meters to 66 meters.

THE MEASUREMENT PARAMETERS OF 7.6 AND 13.6 GHZ

System Parameters		
Frequency Band (GHz)	6.6-8.7	12.98-14.48
Analysis Bandwidth 1 GHz Centered at |(GHz)	7.6	13.6
Sampling Frequency (MHz)	40	
Transmitter Antenna	Omnidirectional	
Tx Antenna Height (m)	2.4	
Receiver Antenna	Omnidirectional	
Rx Antenna Height (m)	1.6	
Record Duration (s)	1	

Measurements scenario

Figure 1 shows the environment of the measurements where (a) shows the receiver in the LoS scenario with the transmitter at the far end whereas Figure 1 (b) shows the position of the transmitter on the side of the building for the NLoS scenario as indicated in Figure 2.

(a) (b)

Fig. 1. The outdoor measurement scenario. (a) LoS case. (b) NLoS case.

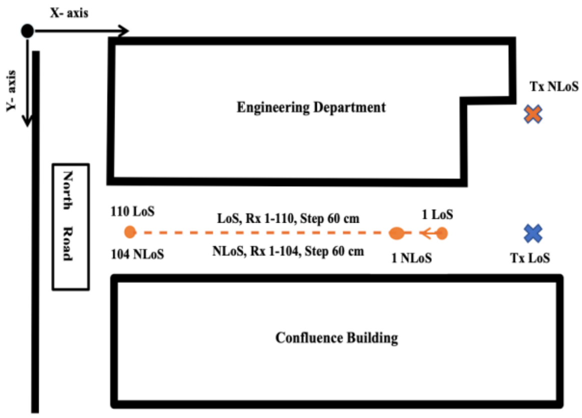
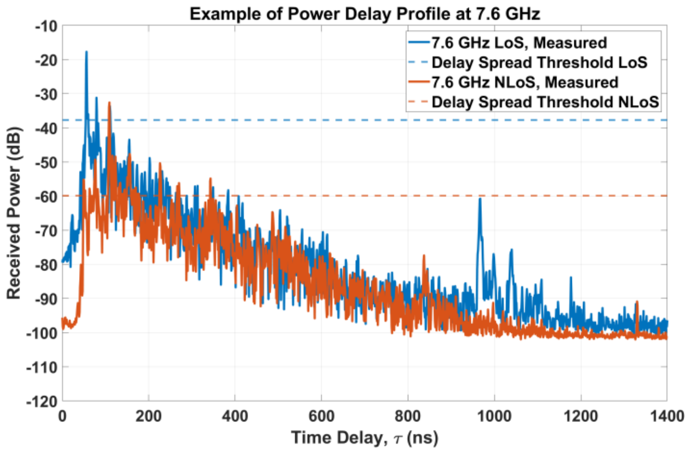


Fig. 2. Layout of the outdoor measurement scenario.

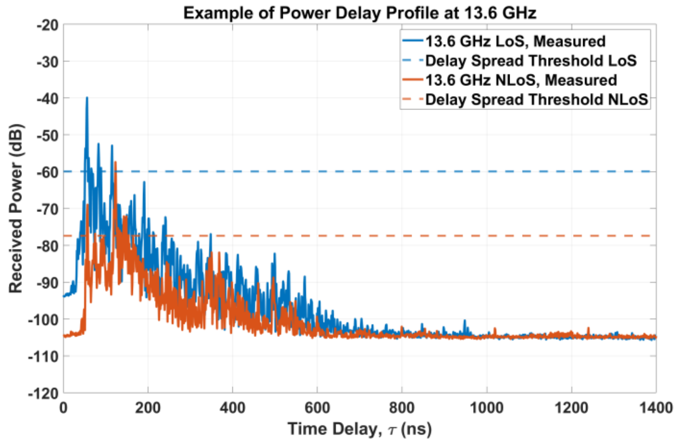
MEASUREMENT RESULTS AND ANALYSIS

PDP and RMS delay spread

Examples of the PDPs for the 7.6 GHz and 13.6 GHz bands are illustrated in Fig. 3 for the LoS and NLoS cases. The figures show that the LoS case exhibits higher received power with fewer components detected, whereas the NLoS PDPs have more multipath components leading to a larger delay spread.



(a)

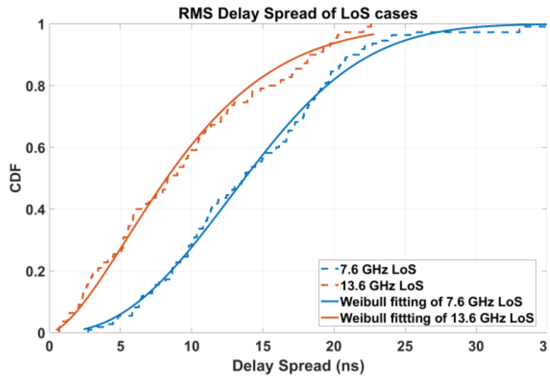


(b)

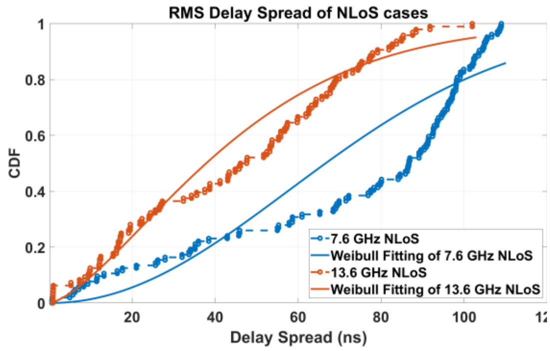
Fig. 3. Single PDP of (a) 7.6 GHz, (b) 13.6 GHz

For the estimation of the RMS delay spread, a 20 dB threshold was set from the peak of each PDP as shown in the dashed lines in Fig. 3.

The cumulative distribution of the estimated RMS delay spread for both scenarios is shown in Fig. 4. for both the LoS and the NLoS cases. The figure shows that in the LoS case, the delay spread of 7.6 GHz band is generally higher than the 13.6 GHz band. Meanwhile, the 7.6 GHz curve exhibits steeper increase between 10 to 20 nanoseconds (ns) range, which indicates that most of the multipath components at 7.6 GHz fall in that time delay range. According to the fitting results, the Weibull fitting curves present a good match for both frequencies in the LoS case. In the NLoS case, both frequencies show larger RMS delay spread with the delay spread at 7.6 GHz exhibiting a wider distribution than the 13.6 GHz band, which indicates that the multipath effect in the channel changed more significantly at 7.6 GHz. Table II provides a summary of the RMS delay spread at the 50% and 90% CDF values.



(a)



(b)

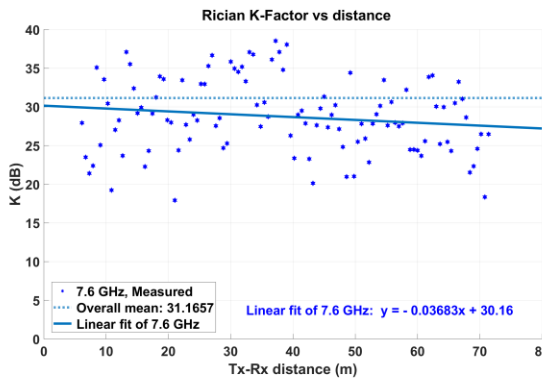
Fig. 4 CDF of RMS delay spread (a) LoS, (b) NLoS.

THE CDF OF RMS DELAY SPREAD

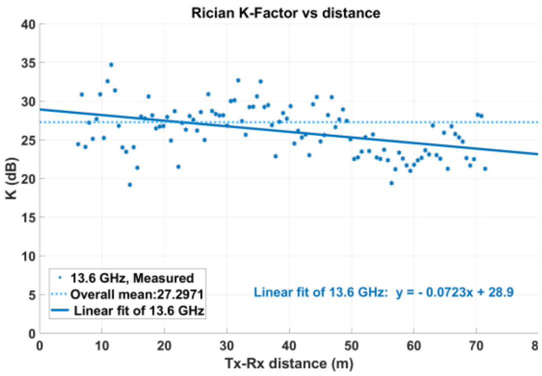
Frequency (GHz)	CDF of Omni RMS Delay Spread			
	LoS 50% (ns)	*LoS 90% (ns)*	*NLoS 50% (ns)*	*NLoS 90% (ns)*
7.6	13.652	22.916	86.671	103.686
13.6	8.298	18.212	46.112	79.159

Rician K-Factor

Fig. 5 shows the scatter plot of the estimated Rician K-Factor vs the Tx and Rx distance for both frequency bands with the overall mean value and a Linear fit for the LoS case.



(a)



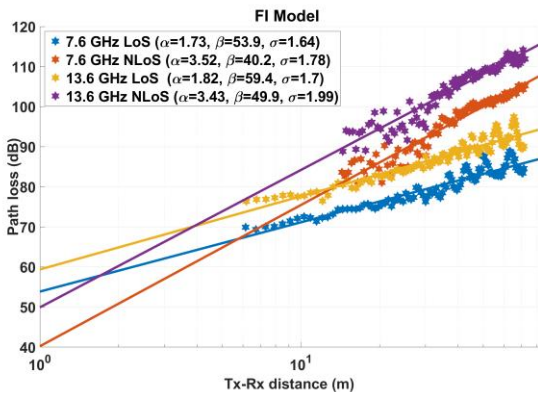
(b)

Fig. 5. Rician K-Factor vs distance for (a) 7.6 GHz and (b) 13.6 GHz

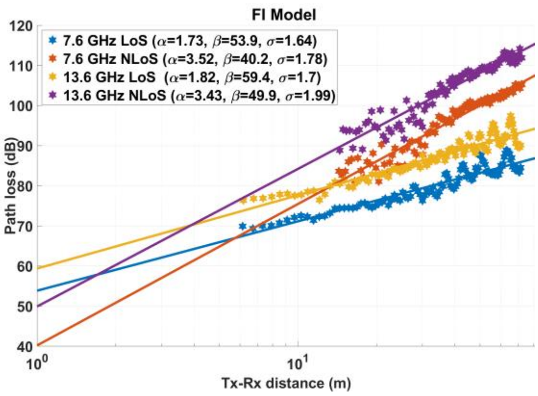
The figures show that the K-Factor, for both frequencies, exhibits a slow decrease as the Tx and Rx distance increases, which indicates the direct LoS signal becomes weaker as the distance increases. The linear fitting results, show that the 7.6 GHz band has a larger value of the K-Factor and a lower slope than that of the 13.6 GHz since the higher frequency band is suffering from more rapid attenuation and path loss.

Path Loss Models and Excess Loss

For the CI and FI models, the corresponding exponents were estimated for both scenarios according to equations (9)-(11). To estimate the received power, a 3 dB threshold level was set above the noise floor of the power delay profile. Fig. 6 illustrates the fitting results for the CI and the FI models. The estimated path loss model parameters are summarized in Table III. Both the CI and FI models indicate a steeper slope for the NLoS scenario compared to the LoS case, due to the higher path loss in the NLoS scenario. The rapid growth of slope in both figures shows that the higher frequency at 13.6 GHz is more sensitive to obstructions and experiences more attenuation as the distance increases, especially in the NLoS scenario. The FI model shows a better fitting result in all cases as the standard deviation is smaller.



(a)



(b)

Fig. 6. Fitting results of path loss (a) CI model, (b) FI model.

THE ESTIMATED PATH LOSS MODEL PARAMETERS

Frequency (GHz)	Sscenario	Path loss Parameters				
		CI Model		FI Model		
		n	σ	α	β	σ
7.6	LoS	1.97	**1.76**	1.73	53.9	**1.64**
	NLoS	2.91	**2.15**	3.52	40.2	**1.78**
13.6	LoS	2.1	**1.85**	1.82	59.4	**1.7**
	NLoS	3.11	**2.08**	3.43	49.9	**1.99**

CONCLUSION AND FUTURE WORK

In this paper, we presented measurement results obtained in a suburban scenario at 7.6 GHz and 13.6 GHz, which are in the range of the newly identified FR3 bands for designing the next generation communication networks. The path loss at both frequencies was analyzed, with the parameters of the corresponding CI and FI models estimated. The FI model shows a more precise fitting result in all cases in particular as indicated by the standard deviation of the fit. The channel parameters such as the RMS delay spread, and the K-Factor were estimated for studying the frequency dependency of the signal, which concludes that the higher frequency bands will be more sensitive to the environmental factors. The path loss measurements will be contributed with further measurements from 0.6 GHz to update the NLoS model in ITU-R P. 1411-12 for the low rise/ suburban scenario which currently starts from 10 GHz.

ACKNOLEWGEMENT

The original sounder was developed under EPSRC grant PATRICIAN, EP/I00923X/1 and extended under EPSRC grant TRACCS EP/W027151/1 to estimate the channel parameters for multiple bands for future deployment indoor and outdoor up to 300 GHz. The upper 6.6-8.7 GHz band was updated under DSIT funding of the Spectrum Sharing Sandbox led by Durham University.

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Ranplan Wireless Network Design Ltd.

Durham University

Feasibility Analysis of Frequency Sharing Between Indoor Wi-Fi and Outdoor Mobile Communications

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Abstract

To address spectrum scarcity, we conducted measurements in outdoor for path loss and indoor building penetration loss using a frequency-modulated continuous wave channel sounder developed at Durham University. The measured results can then be used to calibrate ray tracing simulations, which assess interference between co-channel Wi-Fi and mobile communication signals in indoor and outdoor environments, exploring the feasibility of spectrum sharing.

Introduction

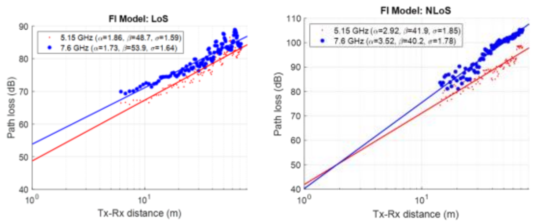
- To explore the coexistence of Wi-Fi and cellular technologies, it is essential to evaluate interference and collisions when both signals operate on the same channel [1].
- To assess signal interference based on path loss characteristics, we conducted outdoor path loss measurements and indoor office wall penetration loss measurements in the upper 6 GHz band.
- These measurements serve as a reference for calibrating signal coverage predictions using ray tracing simulations.

Outdoor Path Loss Measurement

- The outdoor measurement scenarios are shown in Figure 1, including both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions:

Figure 1: The layout of the measurement scenario.

- The transmitter was mounted on a stationary tri-board at 2.4 m height, while the receiver was placed on a trolley at 1.6 m height to simulate a mobile user.
- A total of 110 measurement points were conducted for LoS cases within a range of 6–71.4 m, while 104 points were collected for NLoS cases in the range of 14.4–72 m.



(a) (b)

Figure 2: Path loss model fitting of outdoor measurement results

- Single-frequency Floating-Intercept (FI) models [2] at the measured frequency bands (5.15 GHz and 7.6 GHz) are shown in Figures 2(a) and 2(b), respectively.

Indoor Material Penetration Loss Measurement

- Figure 3 presents the measured penetration loss caused by building materials, providing a reference for the potential interference of indoor signals due to outdoor signal penetration.

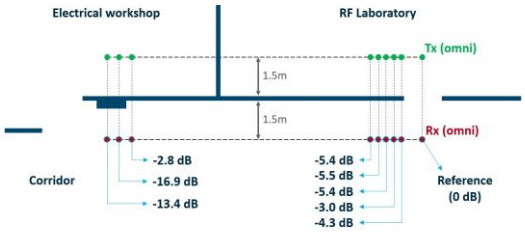


Figure 3: Measurement setup and results of penetration loss

Raytracing Simulation Results

- The simulation scenarios is shown in Figure 4:

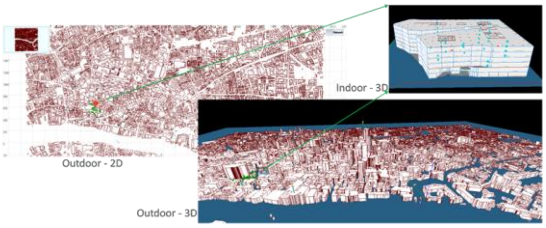


Figure 4: Indoor/outdoor dense urban scenario

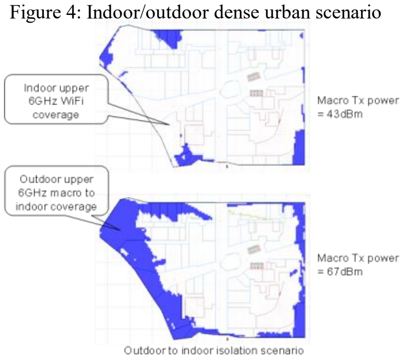


Figure 5: Overlap area from outdoor to indoor

- Reducing the Tx power of outdoor macro cells from 67 dBm to 43 dBm helps isolate the outdoor signal from indoor areas, minimizing overlap and reducing interference from spectrum sharing, as shown in Figure 5.

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Spectrum Sharing in the upper 6G band

Sana Salous[1], Ernest Hocking[2], James Body[2], Jiming Chen[3] and Sion Jones[4]

[1]Durham University, [2]Telet, [3]Ranplan Wireless, [4]London Economics

Abstract

Spectrum has traditionally been assigned by the regulator with an exclusive licence for various services such as mobile network operators (MNOs). This has led to the digital divide with low density populated areas and in particular rural areas being less served by mobile operators. In contrast, Wi-Fi spectrum in the 2 GHz, 5 GHz and lower 6 GHz bands (5925-6425 GHz) are unlicenced with regulation being on the transmitted power. For example in the UK, Ofcom sets the limits typically ranging from 200mW for indoor coverage to 1W for outdoor coverage depending on the frequency band where some bands can be used for both indoor and outdoor communication.

In the International Telecommunications Union (ITU) World Radiocommunications Conference 2023 (WRC-23), the upper 6 GHz band from 6.425-7.125 GHz was proposed for future allocation. In view of this Ofcom has published its vision for hybrid sharing between mobile and Wi-Fi. To study the potential of sharing DSIT funded three sandboxes. In the Sandbox led by Durham University, the following five potential sharing pairs were investigated:

(i) Mobile and WiFi
(ii) Receive-only users (such as scientific applications) and Mobile
(iii) Independently operated private networks in the N77 band
(iv) UWB and Mobile
(v) Mobile and Fixed Links

To address the various aspects of spectrum sharing three work packages were designed with Work package one being led by TRL in collaboration with Telet, Work package two being led by Ranplan and Work package 3 being led by London Economics.

Work Package 1 has explored the use of a cognitive radio approach to achieve spectrum sharing between users in scenarios with low probability of interference. The objective is to build a model of local spectrum usage using the capabilities of the radio requesting spectrum access in order to achieve a rapid response to the presence of RF signals. The work package has proposed a new "permissive licence", sitting between Shared Access License (SAL) and Licence Free modes, that would allow a radio to autonomously operate within a range of frequencies, power levels and bandwidths subject to not interfering with other radio users. target bands for this work are n77 (3.8-4.2 GHz) for indoor use, n46 (5 GHz) and n104 (Upper 6 GHz). Of these bands, n104 currently offers the best opportunity for High Density Deployment, with single 200 MHz channels capable of delivering around 3 Gbps. Due to lack of available n104 equipment, the work package developed a cognitive radio wrapper based on commercial Blinq n46 radio sourced from Canada. This wrapper was able to demonstrate the ability to scan the spectrum for RF signals, analyse the results and then modify the radio's operating parameters to avoid interfering with other base stations. The specification includes a required report to be made to a central spectrum management portal prior to commencement of operation to ensure that regulatory data can be updated dynamically.

In WP2 the Sandbox investigated all the five pairs scenarios to assess the feasibility of sharing the spectrum for example by spatial separation such as for Wi-Fi and mobile separation indoor/outdoor and spatial separation of mobile base stations from astronomy sites which conduct research to study methanol spectral lines in the frequency band 6.65-6.6752 GHz. The modelling simulates spectrum sharing solutions for different system pairs, locations, frequencies, and technologies as well as solutions, and

assess the outcomes. Simulation results show spectrum sharing solution reduces network deployment costs to achieve desired coverage and capacity, and present how cost savings are distributed between system pairs.

To facilitate the simulation in the upper 6 GHz band, radio propagation measurements were conducted in outdoor line of sight and non-line of sight and to measure building entry loss to calibrate the ray tracing tool used in WP2.

The economic analysis for WP3 draws on the network modelling of five small geographical archetype areas in the UK to assess the economic benefits and costs of alternative spectrum allocation regimes – including spectrum sharing - for each of those areas. We also use this analysis to assess the potential aggregate economic impacts at the UK level. The analysis develops counterfactual scenarios where the relevant spectrum bands are not allocated for mobile or Wi-Fi use and compares them with regimes where the relevant spectrum bands are allocated for (i) mobile use only; (ii) Wi-Fi use only; and (iii) shared between mobile and Wi-Fi uses. The analysis is applied to: sharing between mobile and Wi-Fi in the upper 6 GHz band: to provide additional capacity in environments with a high density of simultaneous users at peak times, such as dense urban environments, and high-density sporting or entertainment events.

sharing of other bands with propagation characteristics suitable for wide area provision in lower density areas (e.g. Band III or the n77 band): to facilitate more accessible spectrum for existing MNOs or private network providers to address total and partial connectivity not-spots for mobile users in lower density and rural areas where current network extension is too expensive to deliver.

Preliminary findings suggest that indoor/outdoor spectrum sharing of the Upper 6 GHz band is the spectrum allocation regime with the highest net benefits for the high-density urban area and for the dense urban area. For the sports stadium, allocation of the Upper 6 GHz band to Wi-Fi has a slightly higher benefit than spectrum sharing whilst for the less-dense urban area allocation of the Upper 6 GHz band to mobile has a slightly higher net benefit than

spectrum sharing. We also see net benefits for spectrum sharing across many of the lower density areas analysed, indicating that there are opportunities for network expansion through easier access to spectrum in these areas too. In the case of producers (those who use spectrum to supply services to consumers), these benefits reflect the value of supplying bandwidth to address consumer requirements for throughput at market prices, and for consumers, these reflect their willingness-to-pay for additional coverage and faster data rates. Further analysis will be based on the consultation on the precise mechanisms for authorising the Upper 6 GHz band in 2025.

Spectrum Sharing between UWB and mobile in Upper 6 GHz band

Jiming Chen[1], Sana Salous[2]

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Abstract

As spectrum becomes more crowded, it only makes sense to design for sharing and coexistence by default, to allow for flexibility in meeting as many deployment scenarios as possible in the most flexible manner. The upper 6 GHz band (6425–7125 MHz) has emerged as a critical frontier. While mobile operators seek this spectrum to meet escalating demands for high-capacity, low-latency applications, UWB is a radio technology that is low power and has a relatively high data transfer rate. It operates in wide bandwidths of 500 MHz (or more), currently within the range of 3.1 to 10.6 GHz, which overlaps with upper 6 GHz band. However, due to its orthogonal code characteristics, UWB user power remains below the noise floor, resulting in limited interference with mobile networks. This enables the possibility of simulating and evaluating spectrum sharing between UWB and mobile networks.

1. Interference analysis

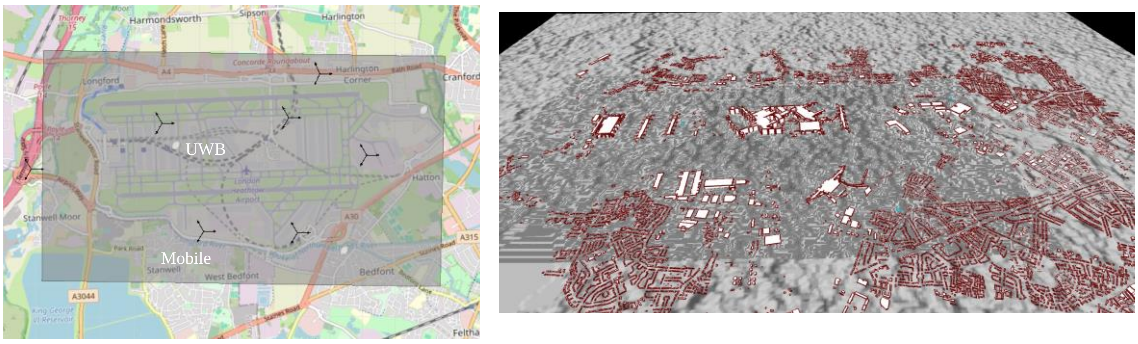
Unlike conventional narrowband systems, UWB operates over a broad frequency range with low transmission power, making it resilient to certain types of interference but more susceptible to environmental obstructions and co-channel coexistence challenges. The total interference threshold for UWB in the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

$$I = P_d - SNR_{min} - Margin \qquad (1)$$

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

2. Simulation analysis

The simulation was conducted with Ranplan Professional[1] tool at London Heathrow Airport, in an environment with high-density wireless activity and large-scale infrastructure that influences UWB propagation characteristics, as in Figure 1, where the location of UWB stations is listed in Table 1.



(a) UWB case in Ranplan Professional

(b) 3D view in Ranplan Professional

Figure 1: UWB and mobile case

The parameters of UWB are defined in Table 1[2-5], where the interference threshold power is -116.6dBm/Hz which means that the mobile signal to UWB station should be less than -116.6dBm.

Table 1: system configuration[5-8]

Parameter	Value
Frequency Band	7000 MHz
Bandwidth	500 MHz
Transmit Power	-41.3 dBm/MHz
Antenna Gain	6 dBi
Received Signal Power (P_d)	-95 dBm
Minimum Required SINR (SNR_{min})	16.6 dB
Additional Loss Margin (Airport Environment)	5 dB
Interference Threshold	-116.6 dBm/Hz

Based on the downlink and uplink reciprocity of path loss, we simulate the path loss of UWB stations to determine the protection area of UWB according to the interference threshold. Assuming the mobile base station EIRP is 58.7dBm/100MHz, the path loss threshold is 93.3 dB to meet the requirement of the received signal threshold being -116.6dBm/Hz.

Figure 2 illustrates the UWB signal distribution and path loss heatmap at Heathrow Airport. The green regions represent areas of strong signal coverage, while blue areas indicate significant signal attenuation caused by obstructions such as airport buildings, terminals, and parked aircraft. The simulation results show that UWB radar requires 150m protection distance due to the unique signal characteristics of UWB. Thus mobile base stations outside the protection distance will have interference level lower than the threshold required by the UWB stations.

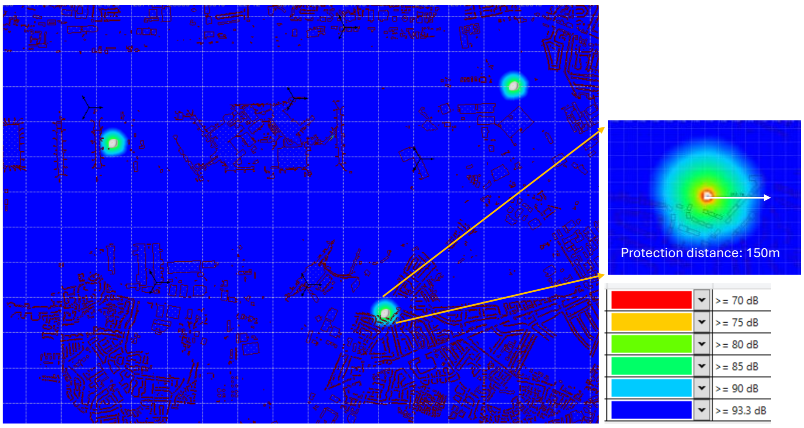


Figure 2: UWB and mobile case simulation results

From the simulation results, there is a small re-usable distance between UWB and mobile due to the unique signal characteristics of UWB. The work provides actionable spectrum sharing insights to reconcile the growing needs of wireless connectivity with the irreplaceable UWB radar system.

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Acknowledgements: This work is part of the Spectrum Sharing Sandbox led by Durham University funded by DSIT.

Case Study of Spectrum Sharing between Mobile and RAS Stations in Upper 6 GHz

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As spectrum becomes more crowded, it is important to consider sharing and coexistence by default, to allow for flexibility in meeting as many deployment scenarios as possible in the most flexible manner. The upper 6 GHz band (6425–7125 MHz) has emerged as a critical frontier. While mobile operators seek this spectrum to meet escalating demands for high-capacity and low-latency applications, Radio Astronomy Service (RAS) stations use parts of the upper 6-GHz spectrum for observations of the methanol spectral line in the band 6650.0-6675.2 MHz, which is addressed in the ITU-R report [1], where the main challenges are considering the coexistence between mobile and RAS stations: i.e. RAS protection criterion and spectrum sharing solutions. Recommendation ITU-R RA.769 [2] gives the methodology to determine the levels of interference detrimental to radio astronomy, with interference threshold as low as -218.1 dBW/50 kHz for the upper 6 GHz band. Using empirical propagation models in 3GPP TR38.901 [3] to simulate the minimum separation distance that allows to protect RAS from aggregate interference of IMT is 60 km with worst-case single interferer urban or rural scenario. Based on the separation distance, the geographic separation of the spectrum sharing solution can be used to share the upper 6 GHz frequence band. In this paper, a simulation framework using ray-tracing propagation models and 3GPP-compliant base station parameters was developed, where ray tracing is used to simulate signal propagation paths to calculate the received power at the RAS station from potential IMT transmitters, considering terrain and obstacles. A case study of RAS at Jodrell Bank Central in UK demonstrates that accurate distance protection can reduce aggregate interference as illustrated in Figure 1.

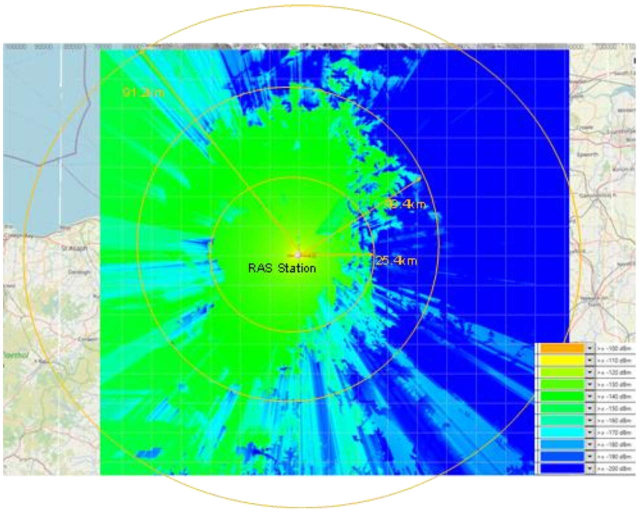

Figure 1 simulation for RAS scenario at Jodrell Bank Central, UK

From the simulation results, the best-case protection distance is about 25.4 km, and larger than 90 km for the worst-case protection distance. This indicates that ray tracing propagation models can accurately predict the protection distance based on the buildings and terrain for potential spectrum sharing solutions. The work provides actionable insights to reconcile the growing needs of wireless connectivity with the irreplaceable scientific value of radio astronomy. Future work will explore AI-driven predictive models for long-term coexistence.

1. ITU-R, “Methods to address the determination of the protection area around existing RAS stations from IMT stations in the frequency band 6 650-6 675.2 MHz,” 2024.
2. Recommendation ITU-R RA.769, “Protection criteria used for radio astronomical measurements,” 2003
3. 3GPP TR 38.901, “Study on channel model for frequencies from 0.5 to 100 GHz,” 2024

25.4km49.4km91.2kmRASStation