Background Radio Noise

Ofcom's long-term radio noise monitoring campaign

Final Report

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Summary

Ensuring the efficient use of spectrum is one of Ofcom's key responsibilities, benefiting both UK consumers and the wider economy. Achieving this requires a detailed understanding of how spectrum is used by services and of factors, such as background Radio Noise, that can affect their performance.

Radio noise[1] is a form of spectrum pollution. It is generated by almost all electronic devices and can degrade spectrum quality, reducing coverage and service performance. To maintain a desired quality of service, it may be necessary to use additional spectrum, increase transmit power or apply a combination of different approaches to mitigate the impact of radio noise.

As electronic devices become increasingly widespread in everyday life, it is becoming more important to measure radio noise and understand its impact. Recognising the limited empirical evidence on radio noise since the 1980s, Ofcom's Spectrum Group published an update report[2] in November 2024 on its long-term measurement campaign that was initiated in 2021 to improve our understanding of the extent and impact of radio noise in the UK.

The measurement campaign concluded in June 2026, and this completion report presents a summary of the overall project. One of the primary outcomes is the development of a novel method for predicting indoor radio noise that has been incorporated into Recommendation ITU-R P.372[3] on Radio Noise. The Recommendation provides guidance that can be used to estimate the impact of different sources of noise on the performance of radiocommunication systems, thereby allowing spectrum regulators to make more effective spectrum management decisions.

The campaign's contributions, findings and conclusions are summarised below.

Radio noise measurement campaign

Ofcom's measurement campaign substantially expands the limited empirical evidence on radio noise at frequencies above 400 MHz, particularly in indoor environments where the use of electronic devices continues to increase. Measurements were conducted in a range of business and residential premises and outdoor environments. Complementary measurements conducted under controlled conditions were used to validate the real-world results and better characterise individual radio noise components.

We have also established a comprehensive database of indoor radio noise measurements. For each monitoring location, the database is supported by a catalogue, recording noise source types, densities, activity patterns and proximity to the monitoring systems.

Campaign findings

The measurement campaign covered the frequency range between ~400 MHz to 1.4 GHz, and noticeable radio noise was observed in all indoor premises and measured frequencies. The measured levels are significantly higher than those reported in the limited historical evidence, or the levels observed outdoors.

[1] Electromagnetic energy generated as a by-product of electric or electronic processes but not intended to produce an information carrying radio signal.

[2] Background Radio noise: Update on Ofcom's long-term radio noise monitoring campaign

[3] Recommendation ITU-R P.372 Radio Noise, https://www.itu.int/rec/R-REC-P.372.

Indoor noise levels exhibit variation by location and time, driven primarily by device density, proximity, and equipment type, as some devices may emit more radio noise than others. Noise levels generally decrease with increasing frequency and distances from noise sources but rise as the number of noise sources increases.

Radio noise levels observed in offices are generally higher than in residential settings. This is largely due to the greater number of devices and computing equipment used within office spaces. During office hours, when more devices are active, the average levels are observed to be twice as high than during non-office hours. In residential settings, as expected, noise levels were significantly higher in areas containing more active electronic devices, such as living rooms and home offices, and lower in less frequently used spaces.

Impact on spectrum users

Below 1 GHz, measured average noise levels were consistently above the typical minimum sensitivity threshold of radio receivers during periods of activity, especially in the offices. This indicates that services below 1 GHz may encounter additional noise above their minimum sensitivity, which can adversely impact their performance.

In general, radio noise decreases as frequency increases. Above 1 GHz, the average levels were below the typical sensitivity of wireless equipment. However, the measurements also showed considerable variation by location and time, with levels increasing where greater numbers of electronic devices are active and under extreme conditions (numerous active devices at very short distances, e.g. < 1 m), the noise levels may exceed the average and impact services.

We found negligible radio noise levels above 400 MHz in the three outdoor locations monitored during the measurement campaign. We also note the monitored locations were quiet compared to outdoor environments with a very high number of noise sources in the vicinity (such as city centres, transport hubs) where the noise level above 400 MHz may be noticeable.

Radio Noise Model

The primary outcome of this project is the development of a prediction method for indoor radio noise. The developed approach addresses the limitations of existing empirical models that classify environments using generalised and subjective categories, such as rural, city-centre, office, etc.

The results of our measurement campaign confirmed that radio-noise levels are influenced more strongly by the presence, characteristics, proximity and activity of individual noise sources than by the nominal use of the building. Consequently, two environments within the same category, such as two offices, may exhibit substantially different radio-noise levels.

The model incorporates key factors influencing indoor radio noise, including source density, source proximity and frequency-dependent radio noise propagation characteristics. This enables calibration of the model across a wide range of indoor environments.

Validation against our extensive measurement data from our long-term campaign demonstrates that the model provides a practical and adaptable framework for predicting indoor radio noise. Its parameters and applicability below 80 MHz and above 2 GHz can be updated as new empirical evidence emerges, providing a simple yet comprehensive framework for spectrum management decisions.

Ofcom's radio noise measurement campaign

Introduction

1.1 Reliable and up-to-date information on radio noise is essential for effective planning and co-existence of radio services. Radio noise arises from both natural phenomena[4] and human-made sources (e.g. ICT equipment). Noise from natural sources is well understood and does not significantly change over time. In contrast, radio noise from human made sources, particularly in indoor environments, continues to evolve with the increasing use of electrical and electronic devices.

1.2 Noise levels in an environment that are above the minimum sensitivity threshold of radio receivers is highly undesirable as it can degrade system performance and increase the cost of deploying and operating wireless systems.

1.3 The Radiocommunication Sector of the International Telecommunication Union (ITU) maintains Recommendation ITU-R P.372[5] which supports international and national spectrum-management frameworks. The Recommendation provides noise figures and equivalent noise temperatures that can be used to estimate the impact of different sources of noise on the performance of radiocommunication systems.

1.4 However, the information in the Recommendation on radio noise from human-made sources was limited and outdated. It was based mainly on a small number of outdoor measurement campaigns undertaken in the second half of the last century, covering frequencies well below 400 MHz. There was a significant gap in understanding of recent trends in radio-noise, particularly in indoor environments, for which little empirical information was available.

1.5 To address the long-standing gap, Ofcom launched a measurement campaign in 2021 to establish radio noise trends across the UK. We published a report[6] in November 2024 that provided an update on the measurement campaign, including preliminary analysis and results.

1.6 Since then, we have expanded the radio noise measurement campaign to more indoor environments and revisited some indoor locations to assess long-term trends. In parallel, we continued contributing measurement data and its analysis to ITU-R Study Group 3[7] (SG 3) as part of our technical contributions to international spectrum management activities.

1.7 The focus of our work was to develop a new modelling approach for predicting indoor radio noise. We have developed a physics-based model that considers key parameters influencing

[4] Events such as lightning discharges, intense solar storms, etc.
[5] Recommendation ITU-R P.372 Radio Noise, https://www.itu.int/rec/R-REC-P.372.
[6] Background Radio noise: Update on Ofcom's long-term radio noise monitoring campaign
[7] Study Group 3 (SG 3), https://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/default.aspx.

radio noise such as distances to observable noise sources and their density, frequency, building types, equipment category and noise propagation paths. We have used the results of our long-term measurement campaign to validate and calibrate this model.

1.8 The results of our research and modelling approach have been published in the peer-reviewed Journal, *IEEE Transactions on Electromagnetic Compatibility*[8] followed by its inclusion in Version 18 of Recommendation ITU-R P.372[9].

1.9 Our novel method provides a robust framework for the prediction of radio noise for frequencies between 80 MHz and 2 GHz for typical indoor environments such as offices, residential, and business premises with standard electric and electronic equipment in use. For premises with specialist and non-standard equipment, the model can be further calibrated based on relevant measurement data.

1.10 Next, we provide a summary of the radio noise monitoring campaign, briefly revisiting the monitored environments and the systems we developed for measuring and characterising distinct components of radio noise (white Gaussian noise (WGN), single carrier noise (SCN), and impulse noise (IN)). WGN represents the relatively continuous background contribution from multiple noise sources, while IN represents less frequent, short-duration events that may have higher amplitudes.

1.11 More details on radio noise and its characterisation, previous measurement campaigns and modelling approaches are provided in Section 1 of 2024 update report.

Monitoring systems for white Gaussian noise (WGN)

1.12 As part of our efforts to establish recent trends of radio noise in the UK, we trialled, tested, and developed appropriate measurement systems for WGN and IN components of radio noise.

1.13 For WGN, we developed six compact monitoring systems to enable automated data collection over extended periods. To enhance system sensitivity, measurements with a small resolution bandwidth of less than 200 kHz were conducted in several channels over a bandwidth of 1-2 MHz in unoccupied or largely interference-free spectrum.

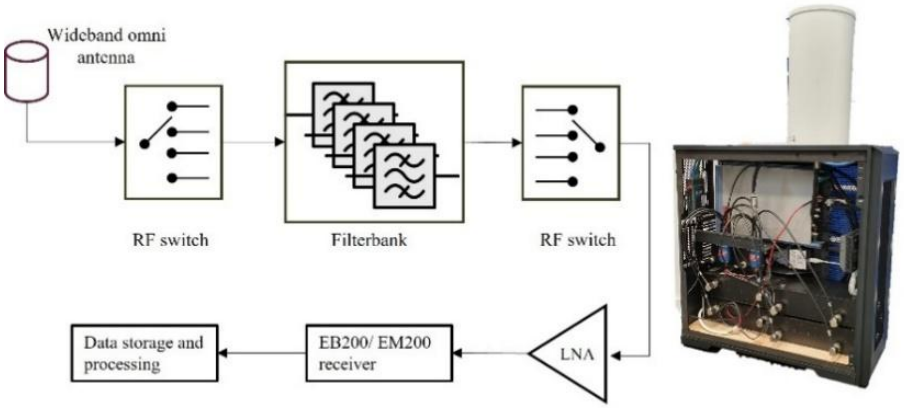
1.14 Each compact unit consisted of a spectrum monitoring receiver, a high-gain low-noise amplifier (LNA), a filterbank with several bandpass filters each tuned at a frequency for monitoring and controlled by RF switches, and a wideband omnidirectional antenna as shown in Figure 1. The overall noise figure (NF) of monitoring systems was around 6 dB, thus enabling the measurement of low levels of noise.

1.15 To capture the full distribution of noise, long-term measurements were conducted to identify daily, weekly, and seasonal patterns of noise sources, allowing both spatial and temporal variations to be analysed. Further details of the WGN monitoring systems and the technical specifications are covered in Annex A1 of 2024 update report.

[8] Prediction Method for Indoor Radio Noise by Human-Made Sources," in IEEE Transactions on Electromagnetic Compatibility, vol. 68, no. 2, pp. 291-301, April 2026,

[9] ITU-R P.372 Radio Noise Section 6.2 Indoor radio noise from man-made sources

Figure 1: Schematic for the compact monitoring systems for white Gaussian noise.



1.16 Another important aspect of our monitoring framework was the data acquisition and analysis methodology. This involved measurement setup, processing, applying various corrections and removal of data that may not correspond to noise. The methodology is captured in Annex A2 of 2024 update report.

WGN measurement approach and locations

1.17 Over a period of six years, radio noise measurements using the compact monitoring systems were conducted in a range of indoor and outdoor environments. The premises where indoor measurements were undertaken include three residential dwellings, and four Ofcom offices in London, Edinburgh, Birmingham and Baldock.

1.18 Outdoor measurements were undertaken at three locations, a) a rural location near our electronics lab in Baldock, b) Wraysbury, a suburban town approximately 5 km from London Heathrow Airport, and c) Ofcom's Birmingham office that is representative of an urban environment. All monitored environments are illustrated in Figure 2.

1.19 To capture the temporal and spatial variability of radio noise, continuous measurements were made for a duration of at least one week in each frequency of interest at multiple locations, covering different areas within each building. In offices, measurement locations were chosen to capture different scenarios, with varying distances between the monitoring system and observable electronic equipment and workspaces including both busy and quiet areas of office activity.

1.20 Measurements in some of the locations were repeated after a period of about six months to determine any noticeable changes to the level of radio noise due to changes in equipment or working patterns. This data collection approach of covering multiple locations helps in determining how radio noise varies within a building and across different building types (e.g., residential versus offices). More importantly, the method provides a means to assess the impact of the variety and density of noise sources near the monitoring location.

1.21 In residential settings, a similar data collection approach is adopted to monitor spaces representative of a typical residential environment in the UK.

1.22 Outdoor measurements are undertaken by installing the monitoring system antenna at a fixed location and making repeated measurements for each frequency of interest. This approach enabled us to capture the long-term temporal variability of radio noise in different outdoor environments.

Figure 2: Background radio noise monitoring locations in the UK.

Outdoor

Urban (Birmingham)



Suburban (Wraysbury)



Rural (Baldock)



Indoor (Residential settings)







Indoor (Ofcom offices)

Birmingham



London



Baldock



Edinburgh



Concurrent indoor and outdoor measurements

1.23 We also undertook concurrent indoor and outdoor measurements at our Baldock and Birmingham offices over a period of six months to better understand the differences between the indoor and outdoor noise levels and the potential contributing sources as illustrated in Figure 3. Indoor measurements were undertaken at multiple locations within the buildings while outdoor measurements were collected with a fixed antenna outdoors.

Figure 3: Concurrent indoor and outdoor measurements.

Ofcom's Birmingham Office





Ofcom's Baldock Office





Monitoring system and approach for IN

1.24 IN characteristics are best captured by employing a raw sampling measurement approach, as it can span large bandwidths. Therefore, measurements should be taken across bandwidths comparable to those of current and emerging services to quantify IN levels, estimate its probability, and assess its impact.

1.25 The primary challenge in measuring radio noise in real-world environments is to ensure that emissions from radio services or non-radio noise signals do not compromise results. Finding free or unoccupied spectrum in the order of tens of MHz is generally possible in very remote rural locations for radio noise measurements.

1.26 We adopted a practical approach by undertaking controlled wideband radio noise measurements in a semi-anechoic chamber by creating a mock office setup at our Baldock electronics laboratory. We used a signal and spectrum analyser and the same wideband passive antenna used by the WGN monitoring systems as shown in Figure 1.

1.27 The equipment used in the mock office setup had the same specifications as used in other real-world offices monitored in this campaign as shown in Figure 4. We acknowledge that a mock setup in a semi-anechoic chamber may not capture the variability of real environments. However, measurements under such settings provide insights that would be unavailable otherwise, and an opportunity for comparison and quality assurance of the measurements in real-world settings.

1.28 Further to our 2024 update report, additional measurements were made across a wide range of frequencies between 400 MHz and 1.4 GHz using varying acquisition bandwidths (ABW)[10] between 1 MHz and 40 MHz to demonstrate and establish how the levels and probability of detection of IN vary with bandwidth. Measurement results from this setting are also used to inform the derivation of the indoor radio noise model as explained later in the report.

Figure 4: Mock office setup inside Ofcom's semi-anechoic chamber at Baldock.



Analysis and results

1.29 In this section, we provide some of the key results that further confirm our in-depth analysis and findings presented in the 2024 update report. We continue to observe a correlation between radio noise levels and the density of active local noise sources in the hundreds of locations monitored within the premises.

1.30 The results consistently show radio noise generally decreases as frequency increases, and beyond 1 GHz, the average noise levels remain below the typical minimum sensitivity threshold of wireless equipment. We start with the findings of the radio noise in real-world indoor premises followed by the key results of controlled measurements inside the semi-anechoic chamber and outdoor environments.

[10] ABW in the context of IQ/raw sampling is the bandwidth that the receiver or analyser uses to capture and analyse the input signal.

Summary of indoor results

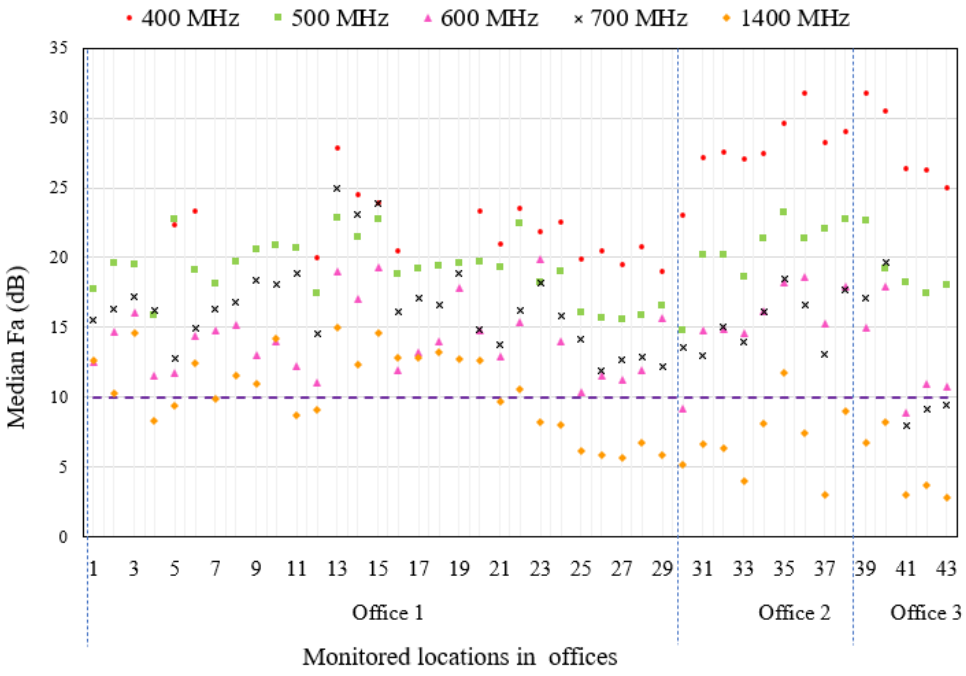
1.31 The monitored frequencies at each premises vary slightly to ensure the quietest range of spectrum is selected for measurements. Consistent with the 2024 update report, the results are presented by rounding the frequencies, e.g. results for all monitored frequencies in the range of 400 to 500 MHz (i.e., 404, 416, 427, 430, 464) are labelled as 400 MHz. We refer to Ofcom's London, Edinburgh and Birmingham offices as Office 1, 2, and 3, respectively.

1.32 The metric for quantifying radio noise is the F_a value which determines the levels of external radio noise above the thermal noise floor. The complete technical details on measurement processing and F_a computation are available in Annex 2 of 2024 update report.

1.33 In Figure 5, the median F_a values at distinct locations monitored in all three Ofcom offices are presented. Each location is monitored for at least one week and the median noise levels across different locations show significant variability. This is attributed to the density and type of equipment in the vicinity of the monitoring system.

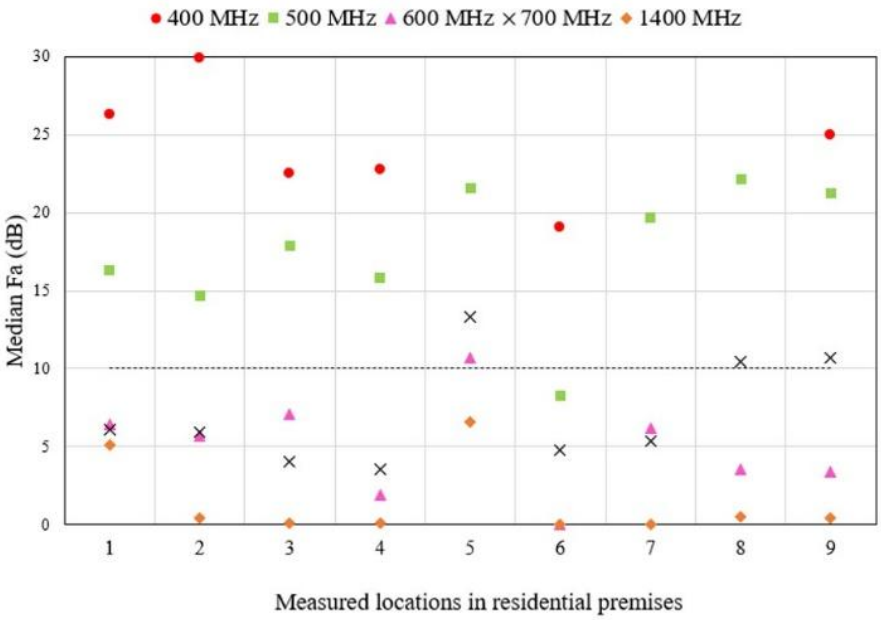
1.34 In general, noise levels tend to decrease with frequency. In most locations, the noise levels for frequencies below 1 GHz are above 10 dB. Offices 2 (Edinburgh) and 3 (Birmingham) show a wider spread of median levels than Office 1 (London). Their 400 MHz levels (red dots) are generally higher, whereas their 1400 MHz levels (yellow diamonds) are lower.

Figure 5: Spatial variability of median F_a across all measured distinct locations in three offices.



1.35 The median F_a values in Figure 6 cover the measured locations in residential settings (living rooms, kitchen, hallways, etc.). The spatial variability is noticeable, however, compared to the median F_a values observed in offices, residential noise levels are much lower, generally falling below 10 dB for frequencies above 500 MHz. The low levels of radio noise can be explained by the lower device densities and smaller physical footprints of homes compared to modern open-plan offices.

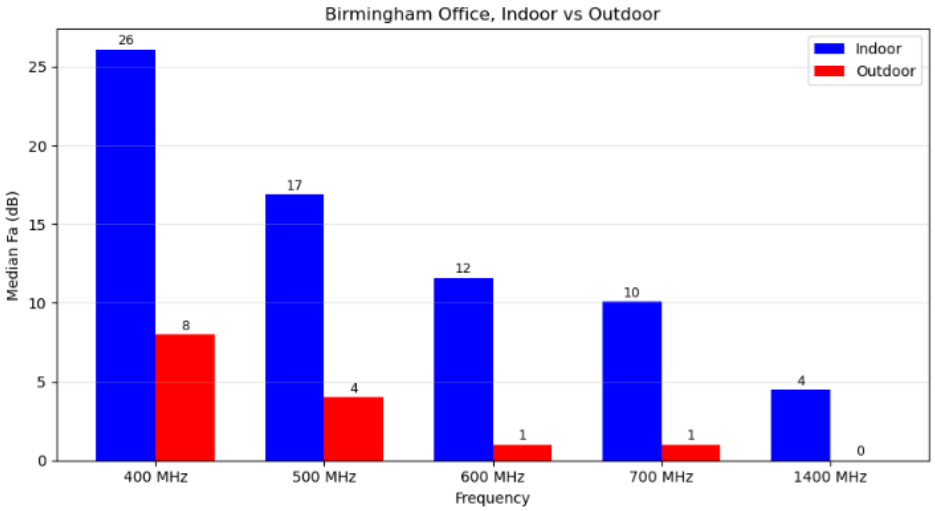
Figure 6: Spatial variability of F_a levels across all measured locations in residential settings.



1.36 We have also compared the median F_a values of indoor measurements across all locations of our Birmingham office with the data collected outdoors over the same period and frequency bands. The results, presented in Figure 7, indicate that the median F_a levels indoors are consistently higher than those measured outdoors. The observed difference strongly indicates that the dominant sources of measured noise originates from indoor electronic devices and IT equipment such as desktops, monitors, network devices, etc.

1.37 The higher indoor F_a values are also consistent with the increased density and proximity of noise sources indoors compared to the location of the outdoor monitoring system's antenna. The measurements were conducted in relatively noise-free bands (i.e., by scanning the spectrum of the bands of interest prior to starting our measurements and tuning the filters of the WGN monitoring unit accordingly).

Figure 7 :Median F_a indoors vs outdoors at Ofcom's Birmingham office.



Summary of Impulse noise results from controlled environment

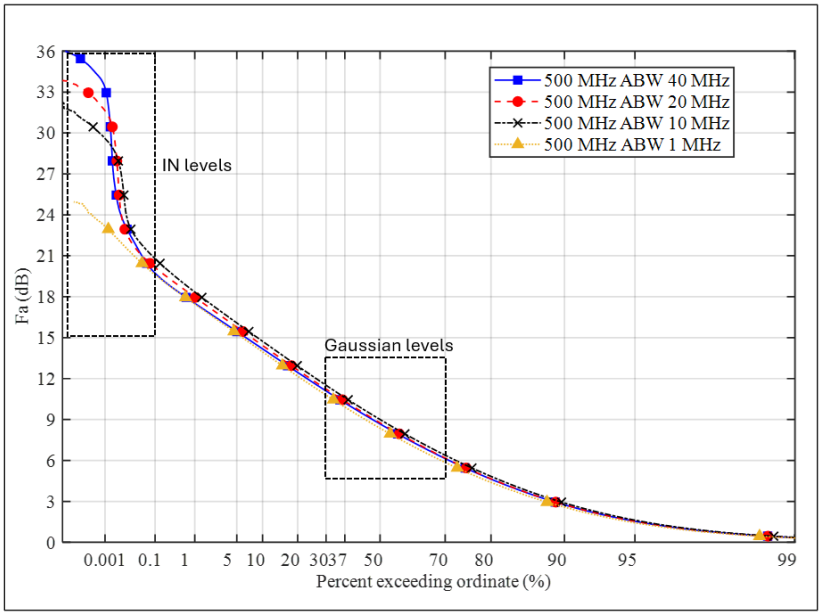
1.38 IN statistics can be accurately depicted using an amplitude probability distribution (APD) plot, which is essentially a complementary cumulative distribution function (CCDF) with Rayleigh scaling applied to the x-axis. This scaling facilitates the identification of various noise components, particularly for low-probability events such as IN. Gaussian noise appears as a straight line under the APD plot's Rayleigh-scaled representation. The presence of IN is indicated by a rising edge in the leftmost section of the graph. The vertical axis denotes the value in dB above the thermal noise floor.

Impact of ABW

1.39 Figure 8 presents the probability distribution of F_a levels on an APD plot for measurements in the mock office setup in the semi-anechoic chamber. All devices are switched on and raw sampling measurements centred at 500 MHz are captured by changing the ABW (or sampling rate) between 1 MHz and 40 MHz to verify the scaling of Gaussian and IN with bandwidth.

1.40 Gaussian levels can be read from the median (~ 37% point) of the APD plot and remain similar across all acquisition bandwidths as Gaussian noise scales linearly with bandwidth. In contrast, IN levels rise as ABW increases, since wider bandwidths capture more of the IN spectral statistics that are not visible at smaller bandwidths.

Figure 8: APD plot comparing the impact of ABW on noise statistics.

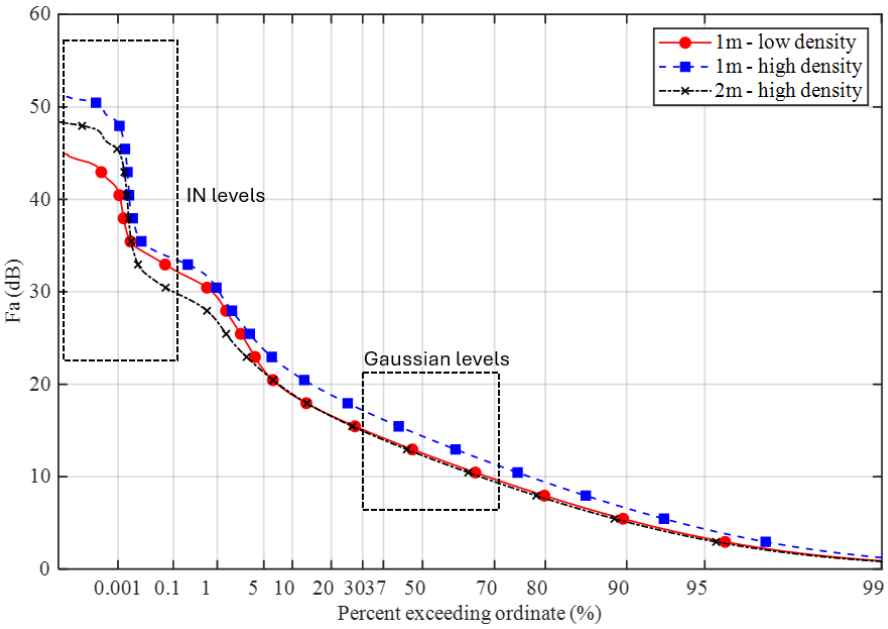


Impact of device density and separation distance

1.41 In Figure 9, the APD plot shows how varying device density and the proximity of noise sources affect the F_a levels. Low device density is emulated by switching on half of the devices in the mock office while high device density corresponds to all devices switched on.

1.42 Raw sampling measurements centred at 400 MHz with an ABW of 40 MHz are taken at distances of 1 m and 2 m from the office setup. At 1 m, high device density produces both higher (~3 dB) Gaussian and higher (~ 6 dB) IN levels compared with the low-density results. Increasing the monitoring system antenna distance to 2 m, reduces the high-density results similar to the low-density levels at 1 m.

Figure 9: APD plot comparing the impact of device density and distance on noise statistics.



Summary of outdoor results

1.43 Our 2024 update report presented outdoor measurement results from a rural site near our electronics lab in Baldock and a suburban site in Wraysbury. The observed radio noise levels were around 7 dB for 400 MHz and became negligible across all monitored bands above 400 MHz. We noted the low levels of radio noise were expected as there is a limited number of active noise sources near the measurement sites.

1.44 We have since deployed one of our monitoring systems with an outdoor antenna at the Birmingham office (c.ref Figure 3) to undertake measurements from a more representative urban environment. The median F_a results presented in Figure 7 based on measurements over a six-month period show a trend consistent with the rural and suburban measurements, with negligible radio-noise levels above 400 MHz.

1.45 The findings further confirm that even in outdoor environments subjective classification such as urban, suburban may not be reliable predictors of outdoor radio-noise levels as they are influenced by the proximity of active noise sources. For frequencies above 400 MHz, the less favourable radio noise propagation characteristics limit the emissions of distant noise sources in outdoor environments.

Indoor radio noise prediction method

2.1 In this section, we present an overview of a novel model we have developed for the prediction of indoor radio noise by human-made sources. The model provides a coherent framework for estimating indoor radio noise between 80 MHz and 2 GHz and has been benchmarked and calibrated using our long-term measurement data. Annex A to this report provides the technical details and supporting numerical framework.

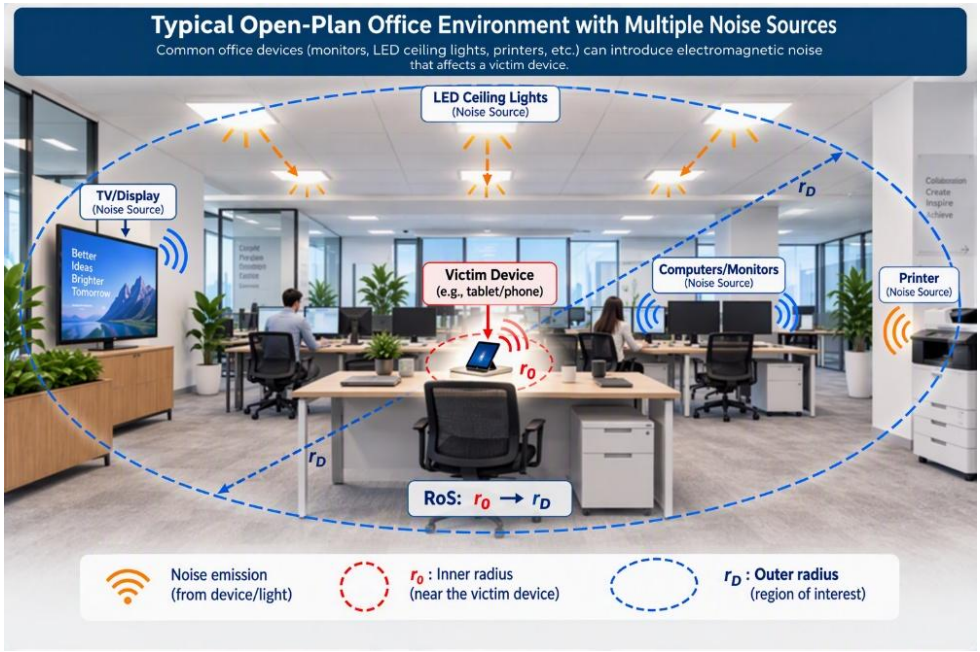
Overview of modelling approach

2.2 Findings from our measurement campaign confirm that indoor radio-noise levels are influenced by the presence, characteristics, and proximity of individual noise sources. Based on this empirical evidence, we have developed a probabilistic model that characterises the distribution of indoor radio noise by incorporating the aggregate contributions of active noise sources and the occurrence probabilities of WGN and IN components.

2.3 The model assumes a typical indoor environment such as an open-plan office, with multiple noise sources distributed around a victim device as illustrated in Figure 10. These sources may include electronic equipment that generates continuous background emissions or intermittent impulsive disturbances depending on their patterns of activity.

2.4 The overall indoor radio-noise environment is therefore represented by a combination of WGN and IN. WGN represents the relatively continuous background contribution from multiple sources, while IN represents less frequent, short-duration events that may have higher amplitudes. The two components are combined using a statistical weighting based on the probability of IN occurrence.

Figure 10: Illustration of typical indoor office environment (AI-generated)



2.5 A radius of significance (r_{D}) defines the area within which sources are considered to make a material contribution with the nearest noise source at a distance r_0. Sources outside the radius of significance (RoS) are assumed to have a negligible effect on the aggregate received noise by the victim device.

2.6 For each source, the received noise is determined by combining its emission characteristics with the frequency-dependent propagation loss between the source and the victim receiver. Indoor propagation loss depends on source-to-victim distance and random variations in the propagation environment. These variations arise from room geometry, building materials, furniture, equipment locations, internal walls and other obstructions.

2.7 The source emissions and indoor propagation losses are assumed to be independent and uncorrelated. The same assumptions are applied to both WGN and IN with different parameter values used to reflect their distinct emission and occurrence probabilities.

2.8 The model further approximates the aggregate radio noise from multiple sources using a lognormal distribution to capture both spatial and temporal variability. Spatial variability results from differences in the number, density, distance and location of noise sources. Temporal variability results from changes in source activity, fluctuations in individual emission levels and the occasional occurrence of IN events. The method therefore predicts a range of possible indoor noise levels rather than a single deterministic value.

2.9 The final output of the model is a cumulative probability distribution describing the likelihood that the indoor radio noise will be below a specified level. This probabilistic output is suitable for studies in which system performance or interference risk must be assessed at a defined reliability level.

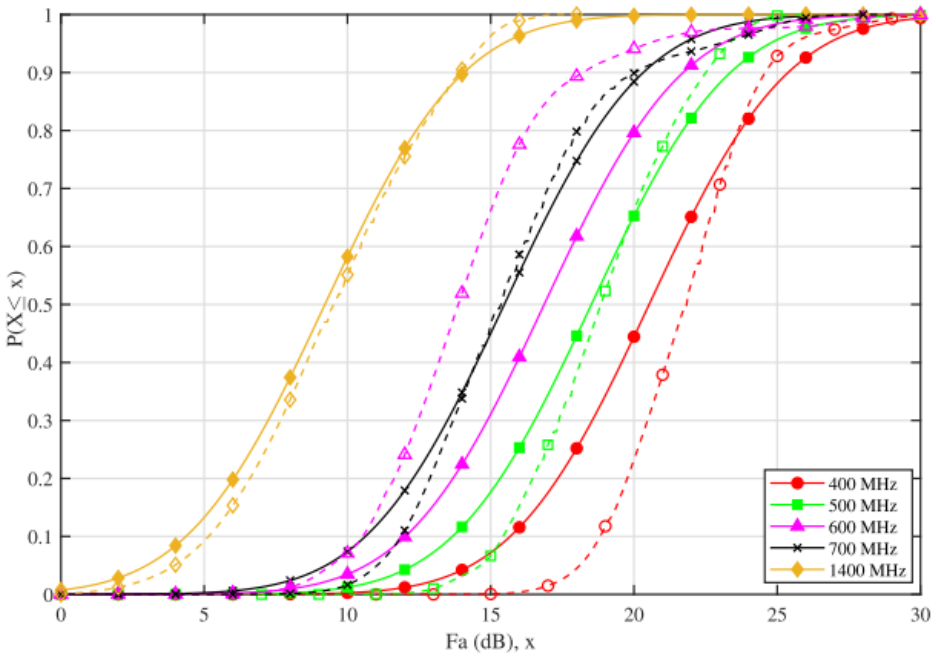
Model output and comparison with measurements

2.10 This section presents selected model outputs and performance comparison against measurements. Model parameters are provided in Table 1 in Annex 1 of this report, and their default values have been established by calibrating the model against Ofcom's long-term measurement campaign.

2.11 The comparison between the predicted and measured radio noise (F_a) distribution for Office 1 (London) is presented in Figure 11. Predictions have been generated by setting the model's RoS parameters as $r_0 = 1$ and $r_D = 4$ m to align with the office environment. A noise source density $\rho = 0.2$ has been assumed, which equates to around nine devices in RoS and broadly aligns with the device density of the office considered.

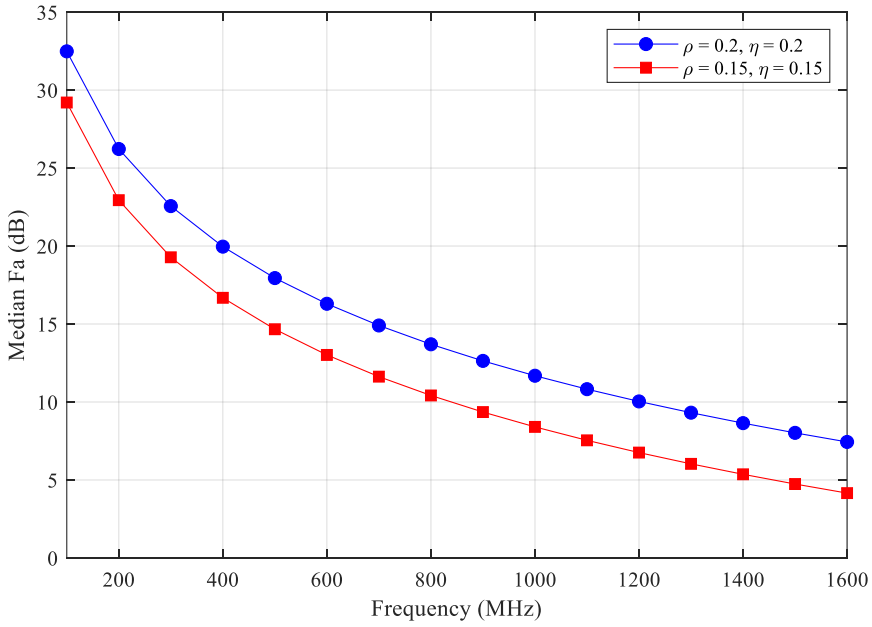
2.12 The average ($\mu_{e,G}$) and variance ($\sigma^2_{e,G}$) of emissions from the noise sources are set to -125 dBm and 2 dB, respectively. Finally, an activity factor, η of 0.2 is chosen and this low activity aligns with the measurements captured over several months, including periods of activity and quiet hours. The comparison shows excellent agreement between predictions and measurements for most frequencies, except 600 MHz where the measured values are lower.

Figure 11: Comparison of distribution of predicted and measured F_a . Solid lines show predictions; broken lines show measurements.



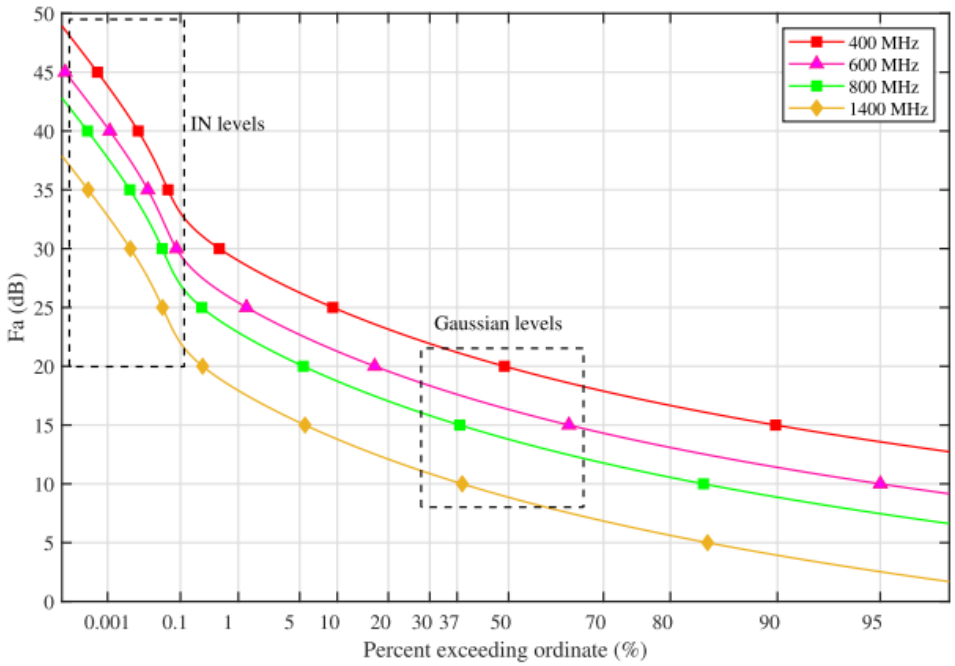
2.13 The model's prediction of median F_a against different frequencies is presented in Figure 12 for different values of noise source densities and activity factors, representative of different indoor environments. A noise source density of 0.2 in RoS broadly aligns with the offices monitored while a lower density of 0.15 is more representative of residential premises.

Figure 12: Predicted median F_a for different device density, ρ, and activity factor, η.



2.14 Finally, in Figure 13, an APD plot shows model output using the default parameters of Table 1 and IN exceedance probability p_i of 0.001. The predictions highlight the flexibility of the proposed model, and its parameters can be further modified and calibrated with empirical evidence.

Figure 13: APD of F_a values predicted by radio noise model for different frequencies.



Concluding remarks

3.1 Ofcom's long-term measurement campaign undertaken between 2021-2026 has provided substantial empirical evidence for understanding the radio noise trends across the UK, particularly within indoor environments. We found noticeable indoor radio noise levels that vary over time and location.

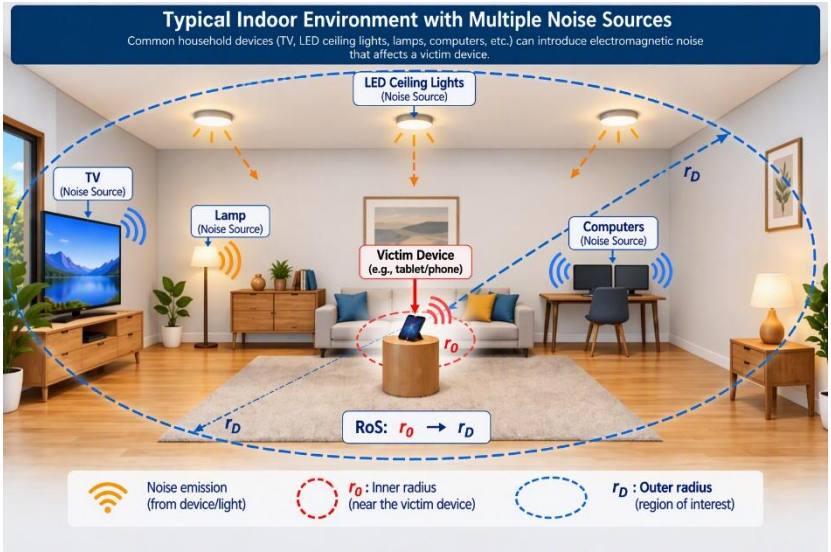
3.2 The results of the measurement campaign highlight that indoor radio noise is determined primarily by the number, type, proximity and activity of electronic devices rather than by broad environment classifications such as office or residential. The findings also identify a potential impact on spectrum users below 1 GHz, where average noise levels during active periods were consistently above the typical sensitivity threshold of radio receivers. However, radio noise generally becomes less significant at higher frequencies and in the outdoor locations measured.

3.3 We have also developed a practical method for predicting indoor radio noise that is grounded in the behaviour of individual noise sources and validated against data collected during the measurement campaign. Its inclusion in Recommendation ITU-R P.372 represents an important contribution to the international understanding of radio noise and provides a more robust basis for service planning, interference assessment and authorisation decisions. The model can be further calibrated and extended as further empirical evidence becomes available.

A1 Indoor radio noise model formulation

A1.1 The model assumes a typical indoor environment featuring multiple noise sources uniformly distributed around a victim device as illustrated in Figure 14.

Figure 14: Illustration of indoor radio noise environment (AI-generated).



A1.2 The model derivation adopts a holistic approach with the assumption that indoor radio noise is composed of all its components. To represent this, a weighted sum of Gaussian distributions is employed, modelling the combined effects of the aggregate Gaussian and impulse noise components. Table 1 provides the model parameters and their default values.

Table 1: Indoor radio noise model parameters

Parameters	Symbol	Unit	Default value
Frequency	f	GHz	-
Distance to nearest noise source	r_o	m	1
Radius of significance	r_D	m	4
Mean Gaussian emission	$\mu_{e,G}$	dBm	-125
Mean IN emission	$\mu_{e,I}$	dBm	-120
Variance of Gaussian emission	$\sigma^2_{e,G}$	dB	2
Variance of IN emission	$\sigma^2_{e,I}$	dB	2
Noise sources' density	ρ	$\#S/m^2$	0.2
Noise sources' activity	η	-	0.2
IN scaling factor	ϵ	dB	-3
Probability of IN	p_i	-	0.001
Basic transmission loss coefficients			
Distance dependent	α	-	1.47
Offset	β	-	34.17
Frequency dependent	γ	-	2.08
Variance	σ_l	-	3.68

Model derivation and formulation

A1.3 A typical indoor environment is assumed where multiple noise sources ($s = 1, \dots, S$) of density ρ and activity η, uniformly distributed around a victim device, with the nearest noise source at a distance r_0. The probability distribution of the distances from all sources is given by:

$$f_R(r) = \frac{2r}{R^2} \tag{1}$$

where R is the bound of the environment.

A1.4 Assuming radio noise components are uncorrelated, the probability of F_a being less than F_x can be expressed as:

$$P(F_a \leq F_x) = \underbrace{p_i P_I(F_x)}_{IN} + \underbrace{(1 - p_i) P_G(F_x)}_{WGN+SCN} \tag{2}$$

where, p_i is the probability of IN, and $P_I(F_x) = P(F_{a,I} \leq F_x)$ and $P_G(F_x) = P(F_{a,G} \leq F_x)$ are the cumulative probabilities of F_a being less than F_x for the IN and Gaussian components, respectively.

A1.5 The proposed model captures the temporal and spatial variabilities of radio noise by considering the probability distributions of contributing factors, as explained next.

Emission from a single noise source

A1.6 The received emissions y_s in dBm from a single noise source s, at a distance r in m can be expressed as:

$$y_s = e_s - L_s(r, f) \tag{3}$$

where e_s is the noise source emission level and $L_s(r, f)$ is the basic transmission loss in dB.

A1.7 The noise source emission, e_s may vary over time and is assumed to follow Normal distribution with means, $\mu_{e,I}$ and $\mu_{e,G}$ and standard deviation $\sigma_{e,I}$ and $\sigma_{e,G}$, for the IN and Gaussian components, respectively. This makes the derivations of $P_I(f)$ and $P_G(f)$ in equation (2) follow the same assumptions and approach, with the differences being the values of the mean and variance of IN and Gaussian components. The distributions for the Gaussian and IN components are:

$$E_{e,G} \sim N(\mu_{e,G}, \sigma^2_{e,G}), \quad E_{e,I} \sim N(\epsilon + \mu_{e,I}, \sigma^2_{e,I}) \tag{4}$$

The IN levels vary with bandwidth (c.f. Figure 8). To capture this variability, a scaling factor, ϵ, is included in (4).

A1.8 The median basic transmission loss $L_s(r, f)$ can be formulated as:

$$L_s(r, f) = \underbrace{(\beta + 10\gamma \log_{10} f)}_{frequency\ dependent\ loss} + \underbrace{(10\alpha \log_{10} r)}_{distance\ dependent\ loss} \tag{5}$$

where:

f: frequency in GHz

α: coefficient associated with the increase of the basic transmission loss with distance

β: coefficient associated with the offset value of basic transmission loss

γ : coefficient associated with increase in basic transmission loss with frequency

A1.9 The distribution of the basic transmission loss for a given distance r can be assumed to follow Normal distribution and expressed as:

$$L(r,f) \sim N\left(\mu_l + 10\alpha \log_{10} r\,, \sigma_l^2\right) \tag{6}$$

where $\mu_l = \beta + 10\gamma \log_{10} f$ and standard deviation, σ_l . The values for parameters α, β, γ and σ_l can be taken from Recommendation ITU-R P.1238 or calibrated further by undertaking indoor environment-specific propagation measurements.

Aggregate emissions from all noise sources

A1.10 The noise received from all sources S is the linear sum of the emissions in milliwatts from individual sources and can be expressed as:

$$\hat{Y}_{all} = \sum_{S} \hat{y}_s \tag{7}$$

where each $\hat{y}_s$ follows a lognormal distribution and the aggregate received noise $\hat{Y}_{all}$ can also be approximated by a lognormal distribution.

A1.11 The received emissions $\hat{y}_s$ from the sth source can be obtained by taking the inverse of the logarithm values of equation (3):

$$\hat{y}_s = \hat{e}_s \hat{l}_s^{-1} r_s^{-\alpha}\,, where \;\; \hat{l}_s = 10^{0.1\beta} f^{\gamma} \tag{8}$$

A1.12 To derive the probability distribution of $\hat{y}_s$, the distribution of each of the three variables, $\hat{e}_s$, $\hat{l}_s^{-1}$ and $r_s^{-\alpha}$ need to be considered. The variables related to noise source emissions, $\hat{e}_s$, and frequency-dependent loss, $\hat{l}_s^{-1}$, can be approximated by a lognormal distribution due to transformation of variables from the logarithm to the linear domain. The pdf of lognormal distribution is given by:

$$f_{\hat{X}}(x) = \frac{\kappa}{x\sigma\sqrt{2\pi}} \exp\left(\frac{-(\kappa \ln x - \mu)^2}{2\sigma^2}\right) \tag{9}$$

where $\kappa = \frac{10}{\ln 10}$ and

$$\hat{\mu} = \exp\left(\frac{\mu}{\kappa} + \frac{\sigma^2}{2\kappa^2}\right) \tag{10}$$

$$\sigma^2 = \left(\exp\left(\frac{\sigma^2}{\kappa^2}\right) - 1\right) \exp\left(\frac{2\mu}{\kappa} + \frac{\sigma^2}{\kappa^2}\right) \tag{11}$$

A1.13 Thus, the means, $\hat{\mu}_{e,I}$ and $\hat{\mu}_{e,G}$ and variances, $\hat{\sigma}_{e,I}^2$ and $\hat{\sigma}_{e,G}^2$ of the source emissions in linear units are calculated by substituting the corresponding variables $\left(\epsilon + \mu_{e,I}\right)$ and $\mu_{e,G}$, and variances, $\sigma_{e,I}^2$ and $\sigma_{e,G}^2$, in (10) and (11), respectively.

A1.14 Similarly, for $\hat{l}_s^{-1}$, mean $\hat{\mu}_l$, and variance $\hat{\sigma}_l^2$ are obtained by replacing μ and σ in (10) and (11) with $-\mu_l$ and σ_l, respectively. By transformation of variable, it can be shown that the distribution of the distance-dependent loss term, $r_s^{-\alpha}$, is given by:

$$f_{R'}(r) = \frac{2}{\alpha R^2}\, r^{-\frac{2}{\alpha}-1} \tag{12}$$

where the mean $\hat{\mu}_r$ and variance $\hat{\sigma}_r^2$ are given by:

$$\hat{\mu}_r = \frac{2}{(\alpha+\zeta-2)\, r_D^2}\left(r_0^{2-\alpha+\zeta} - r_D^{2-\alpha+\zeta}\right) \tag{13}$$

$$\hat{\sigma}_r^2 = \frac{1}{(\alpha+\zeta-1)\, r_D^2}\left(r_0^{2-2(\alpha+\zeta)} - r_D^{2-2(\alpha+\zeta)}\right) - \hat{\mu}_r^2 \tag{14}$$

where r_0 and r_D are the minimum and maximum distances of noise sources to the victim/receiving device, respectively. This can be defined as the radius of significance (RoS) and without loss of generality, $R = r_D$ can be set. The term $\zeta = 10^{-6}$ is the regularisation factor to avoid division by zero in the case $\alpha = 2$.

A1.15 Assuming the variables in (8) are uncorrelated and independent, the mean and variance of the received level from a source for the Gaussian and IN components can be expressed as:

$$\hat{\mu}_{y,G} = \hat{\mu}_{e,G}\, \hat{\mu}_l\, \hat{\mu}_r, \tag{15}$$

$$\hat{\mu}_{y,I} = \hat{\mu}_{e,I}\, \hat{\mu}_l\, \hat{\mu}_r, \tag{16}$$

$$\hat{\sigma}_{y,G}^2 = (\hat{\sigma}_r^2 + \hat{\mu}_r^2)(\hat{\sigma}_l^2 + \hat{\mu}_l^2)(\hat{\sigma}_{e,G}^2 + \hat{\mu}_{e,G}^2) - \hat{\mu}_{e,G}^2\, \hat{\mu}_l^2\, \hat{\mu}_r^2 \tag{17}$$

$$\hat{\sigma}_{y,I}^2 = (\hat{\sigma}_r^2 + \hat{\mu}_r^2)(\hat{\sigma}_l^2 + \hat{\mu}_l^2)(\hat{\sigma}_{e,I}^2 + \hat{\mu}_{e,I}^2) - \hat{\mu}_{e,I}^2\, \hat{\mu}_l^2\, \hat{\mu}_r^2 \tag{18}$$

A1.16 The mean and variance of the aggregate noise in milliwatts are obtained by scaling with the density and activity of noise sources in the RoS and can be expressed as:

$$\hat{\mu}_{y_{all,G}} = \eta\rho\pi\,(r_D^2 - r_0^2)\hat{\mu}_{y,G}, \quad \hat{\mu}_{y_{all,I}} = \eta\rho\pi\,(r_D^2 - r_0^2)\hat{\mu}_{y,I} \tag{19}$$

$$\hat{\sigma}_{y_{all,G}}^2 = \eta\rho\pi\,(r_D^2 - r_0^2)\,\hat{\sigma}_{y,G}^2, \quad \hat{\sigma}_{y_{all,I}}^2 = \eta\rho\pi\,(r_D^2 - r_0^2)\,\hat{\sigma}_{y,I}^2 \tag{20}$$

where $0 \leq \eta \leq 1$ is the activity factor of noise sources; $\eta = 0$ corresponds to the case where the noise sources are inactive and vice versa.

A1.17 Noting the aggregate received noise, $\hat{Y}_{all}$ follows a lognormal distribution, the F_a in dB for the Gaussian and IN components follow Normal distributions due to transformation of variables from the linear to the logarithm domain. Hence, the means and variances are given by:

$$\sigma_{F_{a,G}}^2 = \kappa^2 \ln\left(\frac{\hat{\sigma}_{y_{all,G}}^2}{\hat{\mu}_{y_{all,G}}^2} + 1\right) \tag{21}$$

$$\sigma_{F_{a,I}}^2 = \kappa^2 \ln\left(\frac{\hat{\sigma}_{y_{all,I}}^2}{\hat{\mu}_{y_{all,I}}^2} + 1\right) \tag{22}$$

$$\mu_{F_{a,G}} = \max\left(0, \left(\kappa \ln(\hat{\mu}_{y_{all,G}}) - \frac{\sigma_{F_{a,G}}^2}{2\kappa}\right) + 174\right) \tag{23}$$

$$\mu_{F_{a,I}} = \max\left(0, \left(\kappa \ln(\hat{\mu}_{y_{all,I}}) - \frac{\sigma_{F_{a,I}}^2}{2\kappa}\right) + 174\right) \tag{24}$$

A1.18 The term 174 dBm/Hz is calculated as $10\log_{10}(kTb) + 30$, where the bandwidth b is taken as 1 Hz. Substituting the corresponding variables in (2), the cumulative radio noise distribution can finally be expressed as:

$$P(F_a \leq F_x) = (1 - p_i)\left(1 - Q\left(\frac{F_x - \mu_{F_{a,G}}}{\sigma_{F_{a,G}}}\right)\right) + p_i\left(1 - Q\left(\frac{F_x - \mu_{F_{a,I}}}{\sigma_{F_{a,I}}}\right)\right) \tag{25}$$

where $Q(\cdot)$ is the Q function that represents the tail distribution function of the standard normal distribution.