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(05/2015)

Compilation of measurement data relating to building entry loss

P Series

Radiowave propagation

1865 - 2015

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***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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REPORT ITU-R P.2346-0

Compilation of measurement data relating to building entry loss

(2015)

Scope

This Report provides a compilation of data on building entry loss, and is intended to supplement the material in Recommendation ITU-R P.2040.

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1 Introduction

This Report provides a compilation of empirical data on building entry loss (BEL), and is intended to support the material in Recommendation ITU-R P.2040.

It is also expected that the material in this Report will be of value in the development of new propagation models.

Annex 1 provides information that has been found helpful in planning broadcast and other point-to-area radio services at frequencies below 3 GHz. The contents of this Annex encapsulate measurement data but do not report on a specific measurement campaign.

It should be noted that the measurements recorded in this report have been made using a wide variety of methods. In particular, the definition of BEL may differ from that given in Recommendation ITU-R P.2040. Readers are advised to evaluate the material carefully to ensure that it is appropriate for the purpose intended.

2 Building entry loss measurements (Europe)

Measurements have been carried out in Germany and the United Kingdom to determine values of BEL and other parameters to be used in planning indoor reception of broadcasting services.

The German measurements were made at two frequencies in the VHF band used for digital audio broadcasting and two frequencies in the UHF band. The median values of the BEL over all measurements made in buildings typical for Germany were 9.1 dB at 220 MHz, 8.5 dB at 223 MHz, 7.0 dB at 588 MHz and 8.5 dB at 756 MHz.

The penetration loss from the front of the building (the side with higher signal level) into a room on the opposite side has median values of 14.8 dB at 220 MHz, 13.3 dB at 223 MHz, 17.8 dB at 588 MHz and 16 dB at 756 MHz.

Over all measurements, the median values of the location variation standard deviations are 3.5 dB for the 220 and 223 MHz signals with 1.5 MHz bandwidth and 5.5 dB for the 588 and 756 MHz signals with 120 kHz bandwidth.

The United Kingdom measurements were made at a number of frequencies in the UHF band.

The median BEL at UHF was found to be 8.1 dB with a standard deviation of 4.7 dB. However, the value for rooms on the side of the building furthest from the transmitter was 10.3 dB, whereas the corresponding value for rooms on the side of the building nearest to the transmitter was 5.4 dB; a difference of about 5 dB.

A median value of 13.5 dB was measured for the outdoors height gain between 1.5 and 10 m. The locations of the measurements were suburban.

The median value of the difference in field strength between ground floor and first floor rooms was found to be 5.4 dB.

The standard deviation of the variation of field strength within rooms was about 3 dB.

The standard deviation of the variation of field strength measured for a floor of a house was about 4 dB.

Despite differences in the frequencies and bandwidths of the measurements, there is very good agreement between the German and United Kingdom measurements.

3 Building entry loss measurements (Japan)

Entry loss measurements were made in Japan on 12 office buildings at distances from the transmitter of up to 1 km.

The additional path loss to points within a building was measured relative to the outdoor field averaged along a path around the building at 1.5 m height. Note that the use of the fixed height reference differs from the definition of building entry loss given in Recommendation ITU-R P.2040, and will lead to negative values of entry loss for higher floors of the building.

The data from these measurements has been fitted by the following expression for excess path loss with respect to the averaged 1.5 m value:

$$\Delta Loss(\text{dB}) = 0.41 \cdot d - 0.5 \cdot h - 2.1 \cdot \log(f) - 0.8 \cdot LoS + 11.5 \quad (1)$$

where:

d : 0 to 20 m; the distance from the window (m)

h : 1.5 to 30 m; the height from the ground (m) *f* : 0.8 to 8 GHz; the frequency (GHz)

LoS : 1 for line-of-sight, LoS = 0 for non-line-of-sight.

4 Exit loss measurements

Figure 1 shows a picture of the house used in the measurement. It is a typical bi-level frame house in Japan. The site is approximately 11 m × 12 m. The outer walls have two or three windows on each side. The outside of the exterior walls is covered by painted wooden boards and the inside of the walls are covered with plasterboard. Glass fibre insulation fills the space between inside the walls. A transmitting antenna is set near the centre of the lower floor. The antenna height above the floor level is 1.5 m. A 5.2-GHz continuous wave is transmitted from a vertically polarized dipole antenna. A receiver connected to a dipole antenna is set on a pushcart and moved around the house. The receiving antenna height is set at 2.2 m from the ground level to make it equal in height to the transmitting antenna. Before conducting outside measurements, the received level is measured at several points inside the house.

FIGURE 1

Photo of house

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4.1 Measured result

Figure 2 is a contour map of the received level. High levels are expressed as dark colour and low levels are expressed as light colours. The map shows that intense radiowaves spread out through the windows and propagate to relatively far distances. In this figure, the white part in the upper right corner indicates the location where we could not take measurements due to a barn. The other white part in the upper left side is due to a hedgerow.

FIGURE 2

Contour map of the received level

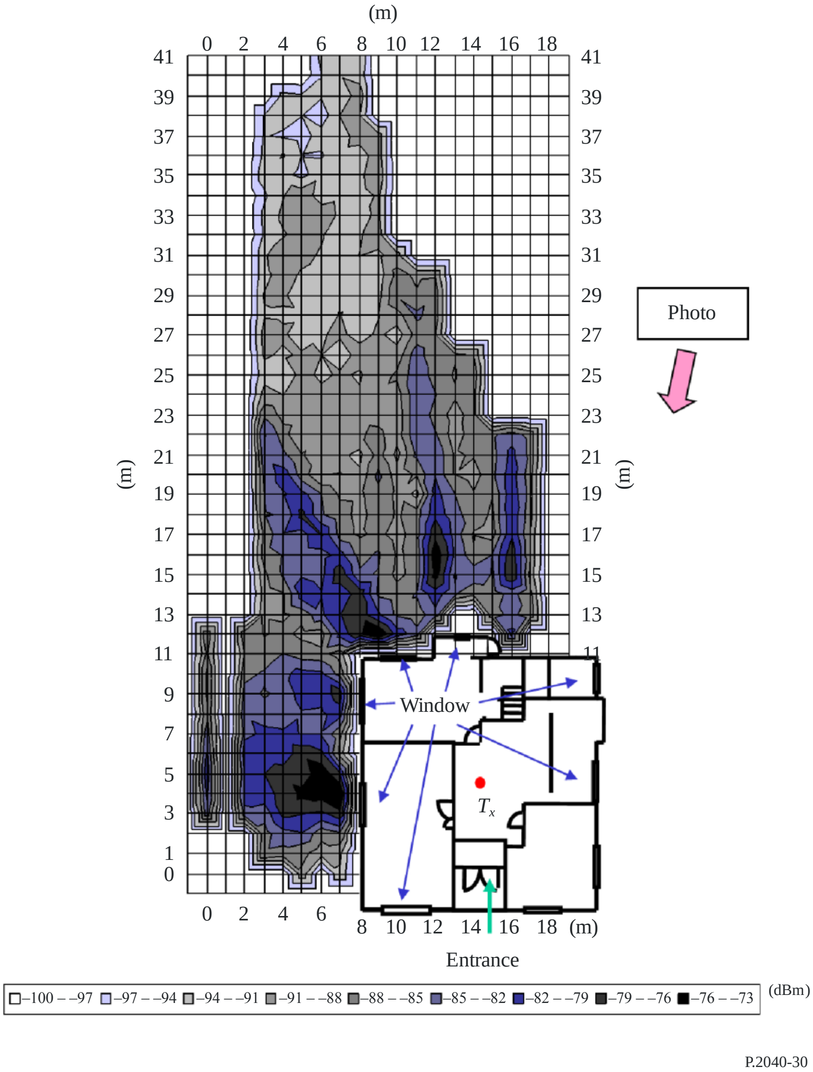


Figure 3 shows the distance dependency of the path loss. The abscissa is a linear scale. The blue circles represent outdoor data and the red triangles represent indoor data. The path loss is approximated by the following equation.

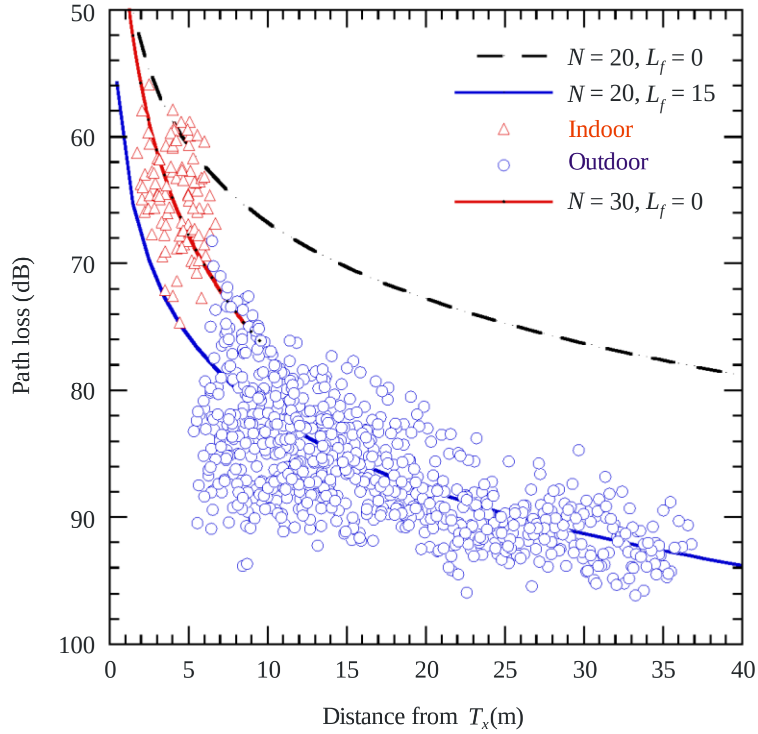
$$L(\text{dB}) = 20\log(f\,(\text{MHz})) + N\log(d(\text{m})) - 27.55 + L_f(\text{dB}) \tag{2}$$

where N is the attenuation coefficient for distance and L_f is the additional attenuation caused by wall penetration for example. When N and L_f equal 20 and 0, respectively, this equation expresses the free-space path loss.

Three calculated lines are shown in Fig. 3. The black dashed line is the free-space path loss at 5.2 GHz. The red solid line approximates the indoor data set. Its L_f equals zero but N equals 30 for a large decline compared to that for free space. The blue solid line has $N = 20$ and $L_f = 15$. The curve parallels that for free-space curve but with a drop of 15 dB. This result indicates that the path loss increases with a large N within the house and the increase becomes gradual after it exits the house. This feature is clearly observed in Fig. 3.

FIGURE 3

Distance dependencies of the path loss (linear scale)



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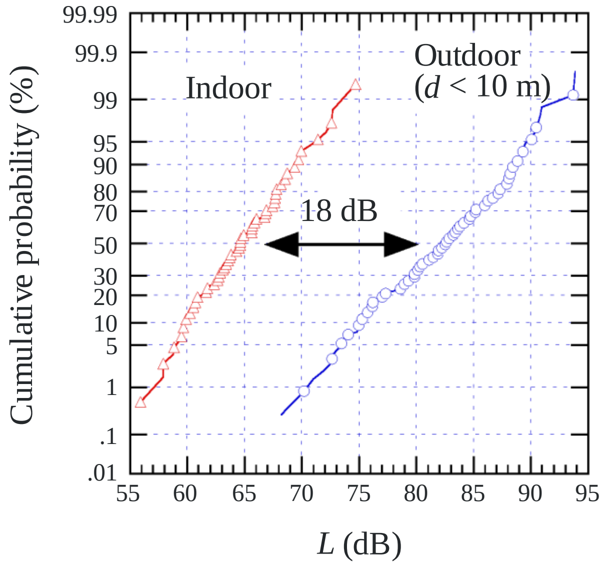
Based on these data, cumulative probabilities of the path loss are derived in Fig. 4. The difference between these two probabilities is approximately 18 dB. This indicates that the radiowave exits from the house with an attenuation of approximately 18 dB and propagates with the same attenuation coefficient in distance as that for free space.

FIGURE 4

Cumulative probabilities of measured path loss data



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5 Building entry loss – slant path measurements

5.1 UHF satellite signal measurements (860 MHz – 2.6 GHz)

Representative UHF satellite signal attenuation observed within rooms located near an exterior wall in timber-framed private homes is summarized in Table 1. For interior rooms, 0.6 dB must be added to the tabulated values. For timber-framed buildings the attenuation shows little variation with weather or path elevation angle but, as the Table illustrates, there is a systematic variation with frequency, polarization, construction materials, insulation and position within the structure. Some aluminium-backed insulating and construction materials contribute up to 20 dB of loss.

TABLE 1

UHF signal attenuation (dB) through timber-framed buildings*

Building condition		**Frequency (MHz) and polarization (Horizontal: H, Vertical: V)**			
Exterior	Insulation (non-metallic type)	860 H	860 V	1 550 V	2 569 V
Wood siding	Ceiling only	4.7	2.9	5.0	5.8
	Ceiling and wall	6.3	4.5	6.6	7.4
Brick veneer	Ceiling only	5.9	4.1	6.2	7.0
Bricks	Ceiling and wall	7.5	5.7	7.8	8.6

* The Table is for rooms located near to the exterior wall; for interior rooms, 0.6 dB should be added.

5.2 Slant-path measurements from towers or high rise buildings

Measurements of building entry loss using 18 to 20 m towers to simulate a satellite transmitter were performed in the bands 700 MHz to 1.8 GHz and 500 MHz to 3 GHz to determine the mean loss and spatial variability in a variety of buildings. There are insufficient data to give precise prediction methods, but the data in Tables 2 to 3 are indicative.

TABLE 2

Signal distributions at the average position and best position within buildings (over the frequency range 700 to 1 800 MHz)

Building number	Construction	Elevation angle	Average position		Best position	
			Mean loss (dB)	Standard deviation (dB)	Mean loss (dB)	Standard deviation (dB)
1	Corner office, large windows, single-story building. Concrete block, plasterboard, double-glazing. Concrete roof on steel beams	27.5° (LoS through window, azimuth angle between wall and LoS is 50°)	7.9	5.5	4.2	4.2
2	Small room with windows being 5/8 of exterior wall	18° (LoS through window, azimuth angle between wall and LoS is 50°)	9.1	4.4	5.4	3.7
3	Corner foyer, large reflective glass door in half of one exterior wall. External walls concrete, internal walls plasterboard on metal frame	16° (LoS through window, 45° azimuth angle between one wall and LoS, both exterior walls illuminated by transmitter)	15.4	8.4	9.7	6.7
4	Sheet metal shack with plywood interior. One small unscreened window on each of two sides, metal-covered door	25° (azimuth angle between wall and LoS is 60°)	9.7	6.3	5.2	4.9
5	Two-story wood-side house, rockwool insulation (walls and attic); gypsum board, no metallic heat-shield. No metallic screens on windows. Wood-shingled roof	25° (azimuth angle between wall and LoS is 45°)	9.0	4.5	5.4	3.7
6	Empty sheet-metal mobile trailer home, metal frame windows with metal screens	25° (azimuth angle between wall and LoS is 45°)	24.9	3.8	19.8	3.4

TABLE 3

Median loss at the average position and best position within buildings as a function of frequency (Construction details and elevation angle as in Table 2)

Building number	Average position	Best position
(As in Table 2)	750-1 750 MHz	750-1 750 MHz
1	5-11 dB	2-6 dB
2	5-14 dB	2-5 dB
3	17-18 dB	12-13 dB
4	9-11 dB	5-6 dB
5	5-11 dB	3-5 dB
6	20 to > 24 dB	16-22 dB

TABLE 4

Signal distributions at the average position within buildings (estimated over the frequency range 500-3 000 MHz)

Building number	Construction	Elevation angle (degrees)	Average position	
			Mean loss (dB)	Standard deviation (dB)
1	Entry lobby in single storey building – concrete tilt wall, tar roof	18	13	10
2	Office in single storey building – block brick, tar roof	38	9	7
3	Two-storey wood frame farmhouse, metal roof, no aluminium heat-shield	33	5	4
4	Hallway and living room of two-storey woodframe house, metal roof, aluminium heat-shield	41	19.5	12
5	Motel room in two-storey building, brick with composite roof	37	13	6
6	Lobby of two-storey building, glass and concrete, tar roof	26	12	5

In the first set of measurements (Tables 2 and 3), the first three buildings had elevation angles such that the room was illuminated through a window with a direct LoS from the transmitter. The elevation angles were below 30° to allow side illumination of the buildings.

In the case of building number 3 in these tables, losses through the reflective glass door were about 15 dB greater than when the door was open.

The results of another study are similar, with mean attenuation levels (in the frequency range 500 to 3 000 MHz) varying between 5 dB for a woodframe house with metal roof and no aluminium heat-shield, to 20 dB for a similar house with an aluminium heat-shield. Table 4 shows a summary of the measured mean attenuation values.

Note that for some of the measurements, values obtained near a window or an open door, are included in the averaging. In the motel (building 6), attenuation when the direct path penetrated a brick wall was 15 to 30 dB below the LoS value. Levels inside building 4 varied from 25 to 45 dB below the LoS value, due to the metal roof and aluminium heat-shield.

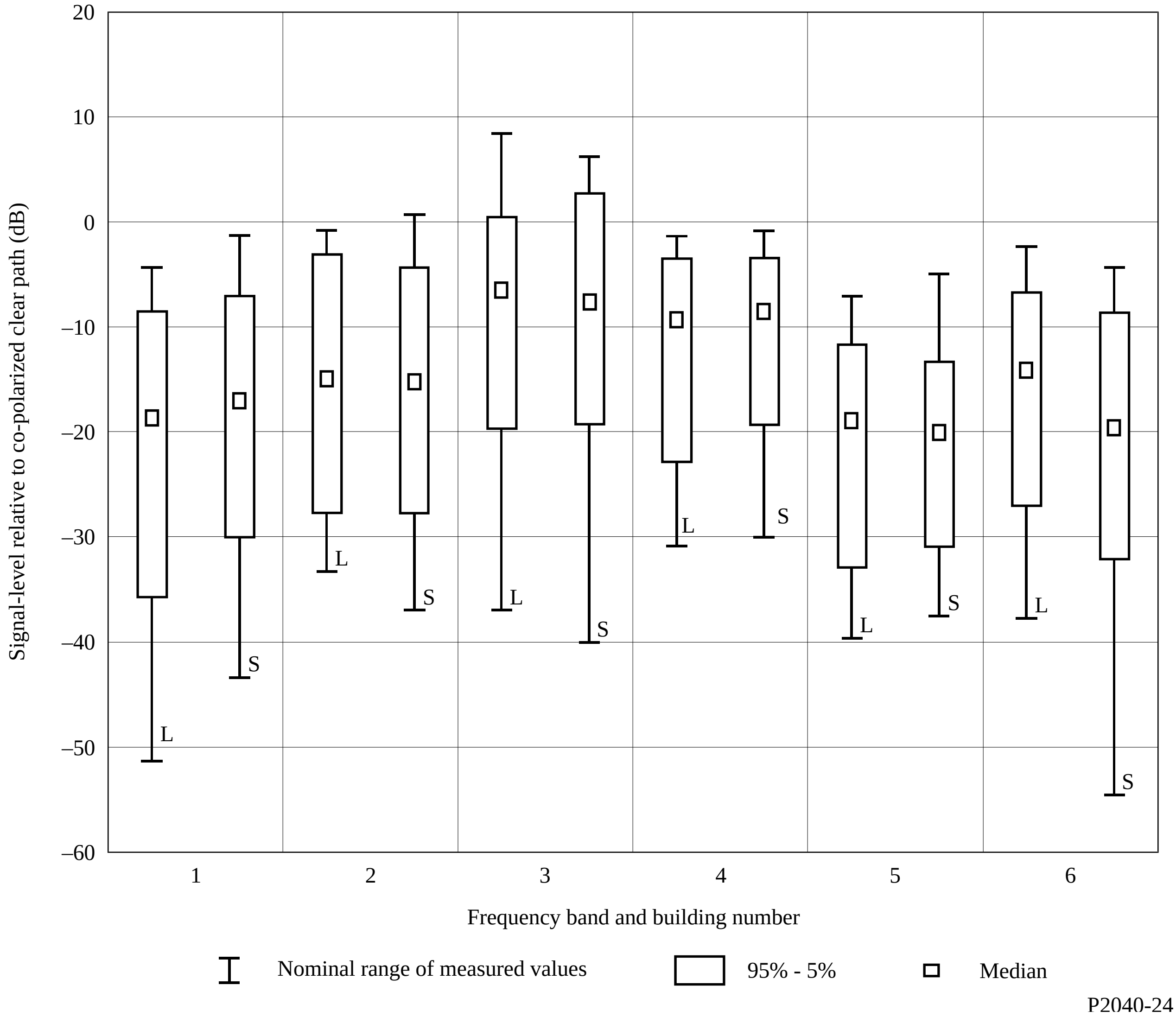
Note also that the measurements were on stationary paths. There is evidence that close-in multipath effects will give rise to fluctuations in received signal level should the transmitter or receiver move. This has implications particularly for low-Earth orbit (LEO) systems where the transmitter is moving rapidly with respect to the receiver.

The measurements indicate that attenuation increases with frequency by about 1 to 3 dB/GHz in buildings 1, 2, 4, and 6, by 6 dB/GHz in the least attenuating building (building 3), and shows almost no change with frequency in the glass-walled building 5. Since the values given above are averaged over the frequency range 500 MHz to 3 GHz, they are expected to be slightly optimistic for the 1 to 3 GHz range.

For the six buildings identified in Table 2, 1.6 GHz and 2.5 GHz measurements were performed and analysed to determine the median, 5% and 95% levels of relative signal loss when the antennas were moved horizontally over multiple 80 cm intervals. The buildings were illuminated from the side, and the signals received inside the outside wall (one-wall entry). Azimuthally omnidirectional antennas were used to receive the transmitted signals. Statistics derived from these measurements are summarized in Fig. 5. These data indicate the magnitude and variations of fading that are possible for signal transmission through building walls. Note that on occasions, multipath conditions yield relative signal levels in excess of 0 dB.

FIGURE 5

Median, 5% and 95% levels of building entry power loss relative to unobstructed LoS at 1.6 GHz and 2.5 GHz for the six buildings identified in Table 2 (designated by 1 to 6 in the Figure).
For each building, the 1.6 GHz (L) and 2.5 GHz (S) statistics are shown separately



None of the available measurements at frequency bands below 3 GHz provides information for elevation angles above 41°. However, the large losses through metal structures (building 6 in Tables 2 and 3; building 4 in Table 3) suggest that attenuation for a direct path through a metal roof will be of the order of 20 dB. The losses of 15 to 30 dB for a brick wall in building 4 of Table 3 are relevant for higher elevation angles as well.

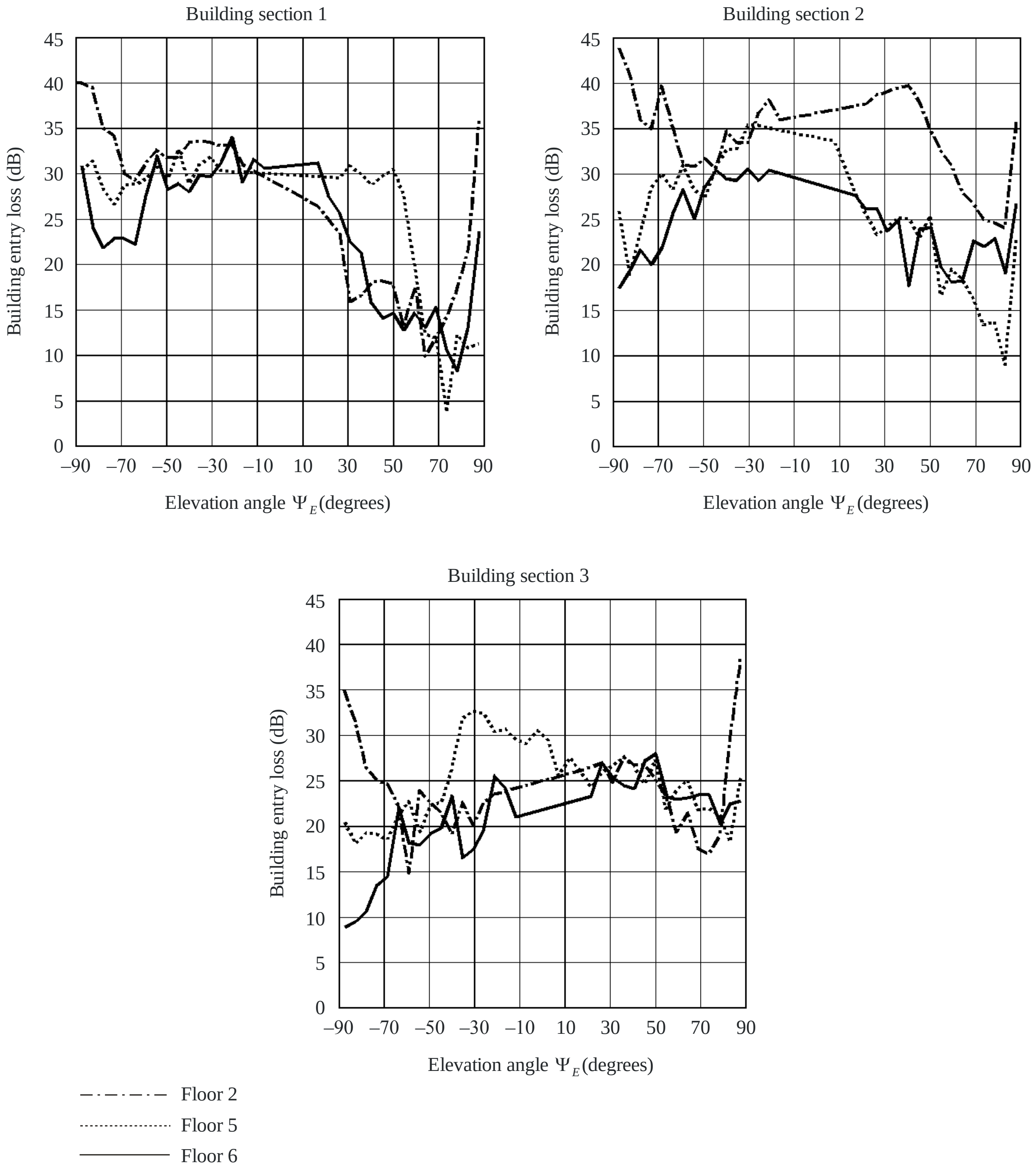
The elevation angle dependence of building entry loss was measured in the 5 GHz band at two different elevation angles by using high-rise buildings to simulate the reception of satellite signals. In an office-type room, the measured medians of the excess building entry loss were 20 dB and 35 dB for elevation angles of 15° and 55°, respectively.

5.3 Helicopter measurements to office building

The elevation and azimuth angle dependencies of building entry loss around 5 GHz were measured at different positions within an eight-storey building on three different floors. A helicopter was used to simulate a satellite transmitter. The received signal was continuously recorded, as well as the position of the helicopter by means of a differential global positioning system (GPS) receiver. The experimental conditions and averaged measurement results are summarized in Table 5. The behaviour of the building entry loss with respect to path elevation angle is shown in Fig. 6, and the behaviour with respect to azimuth in Fig. 7 for elevation angles of 15° and 30°.

FIGURE 6

Building entry loss at 5.1 GHz at sections 1, 2 and 3 for floors 2, 5 and 6. The angle Ψ_E is positive-defined when looking to the north and negative-defined to the south
$|\Psi_E| = 90° - \varepsilon$ where ε is the elevation angle



Building section 1: rooms with windows facing helicopter transmitter.

Building section 2: center of corridor.

Building section 3: rooms with windows not facing helicopter transmitter.

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FIGURE 7

Building entry loss at 5.1 GHz for elevation 15° and 30° at the four different indoor antenna positions. Numbers 1 and 2 are located close to an outer wall, whereas numbers 3 and 4 are located in the corridor

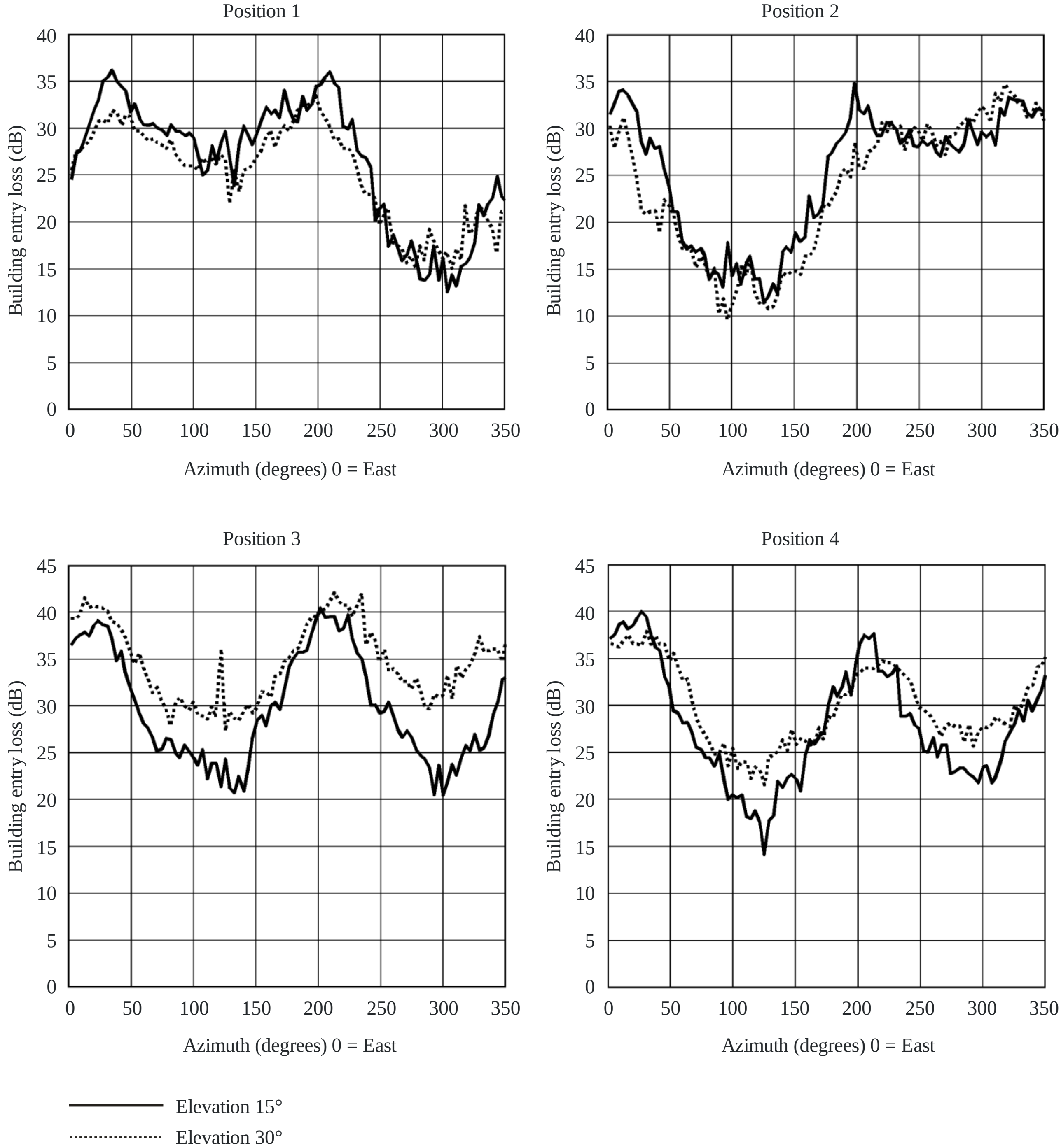

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TABLE 5

Average median building entry loss and observed range of the median building entry loss measured at 5.1 GHz for different positions in an office building

	Type of measurements (helicopter trajectory)	**Average of the median building entry loss for different receiver positions in the building (dB)**	**Observed range of the median building entry loss (dB)**
Eight-storey building with seven storeys above ground and one extra storey placed on the former roof, brick-walls and windows placed in strips: behind the brick-wall there is a 10 cm thick concrete wall; windows made of two layers of plain non-thermal glass, storeys separated by 3.5 m with 2.5 m from floor to ceiling, two layers of plaster with wooden laths in between separate the rooms; interior walls facing the corridor are in most cases made of glass, rooms commonly furnished with desks and bookshelves; each storey has three sections, a corridor with office rooms at the sides	Elevation angle measurements (linear, perpendicular to the long side of the building)	19.1	~ 5-45
	Azimuth angle measurements (circular at elevation angles of 15° and 30°)	22.3	~ 10-42

Measurements at 2.57 GHz and 5.2 GHz using an igloo shaped flight pattern were performed inward to three different buildings, one of them in the Graz/Austria area, another two in the Vienna/Austria area, covering various building types. The transmitter was carried by a helicopter, on which a steerable helix antenna was mounted. The measurements were performed with a high resolution, pseudo random sequence based channel sounder with a chipping rate of 100 Mcps and 200 MHz bandwidth. The transmit antenna was right-hand circularly polarized (RHCP) while the receive antenna for the channel sounder case consisted of a set of patch antennas with two orthogonal linear polarizations covering a surface that approximates a semi-sphere.

Table 6 gives an overview of the inward building locations.

TABLE 6

Overview on buildings measured

Building		**Location**	**#RX locations**	**Façade/roof material**
Millennium Tower skyscraper	22nd floor 44th floor	Vienna	2 2	Metal grid and glass panels, coated glass with sun protective layer/Reinforced concrete
Graz airport	Gate Area Conference room	Feldkirchen near Graz	4 1	Steel, metal construction elements, coated glass with sun protective layer/Steel, metal sheets, layer of gravel
Office building FFG	Inner city office building, highest floor	Vienna	2	Reinforced concrete/coated windows

The building entry loss shown in Table 7 was calculated by subtracting the Average Power Delay Profile from an outdoor reference measurement from the Average Power Delay Profile measurement inside the buildings. The building entry loss for various distances to the window directed to the transmitter at 5.2 GHz is presented in Table 8.

TABLE 7

Entry loss (dB) for different elevation and relative azimuth angles at 2.57 and 5.2 GHz

Building	Relative azimuth to facade normal	2.57 GHz				5.2 GHz			
		Elevation				Elevation			
		15	30	45	60	15	30	45	60
Millennium Tower 44th floor	0	22.86	24.42	21.53	23.95	30.40	27.65	32.09	29.77
	–30	22.13	22.17	25.21	24.59	28.34	30.42	32.43	33.31
	–60	24.44	23.71	25.91	24.60	29.00	31.31	33.57	34.97
	–90	25.40	29.24	27.21	26.77	32.65	34.23	37.24	38.21
Millennium Tower 22nd floor	0	28.04	28.31	28.13	28.28	36.53	37.55	35.38	39.45
	–30	28.70	29.60	29.60	27.59	31.84	36.57	37.51	35.34
	–60	32.26	33.17	33.66	35.38	35.19	37.12	35.90	39.65
	–90	35.30	42.22	37.80	–	43.20	43.80	47.02	46.52
Office Building	0	21.69	29.23	26.18	31.40	26.52	31.13	34.13	35.28
	30	26.49	34.90	31.10	33.00	33.12	33.49	36.51	34.08
	60	27.43	–	35.90	36.13	34.29	34.16	36.30	35.73
	90	–	38.09	–	–	–	–	–	–
Airport – Gate Area	0	18.18	–	23.68	23.00	28.36	35.76	–	37.97
	–30	15.09	21.12	19.11	27.10	–	–	–	37.98
	–60	18.25	26.13	21.96	25.42	27.67	37.76	–	–
	–90	–	27.71	23.69	24.61	34.31	–	–	–
Airport – Conference Room	0	11.81	12.62	–	10.84	15.19	19.68	19.37	19.09
	–30	11.69	–	15.05	13.63	17.73	19.37	20.03	–
	–60	16.65	17.87	17.66	16.35	22.79	–	24.70	22.38
	–90	18.52	20.10	17.43	–	25.17	24.32	23.43	–

TABLE 8

Entry loss (dB) at 5.2 GHz for different elevation angles relative to the distance to the window directed to the transmitter located at 0 degrees relative azimuth angle to the façade normal

Building	Distance to window (m)	Elevation			
		15	30	45	60
Millenium Tower 44th floor	1.4	–	25.30	31.41	27.80
	2.4	–	27.34	31.16	27.81
	3.4	–	29.72	31.64	30.58
	4.4	–	25.6	32.19	28.88
	5.4	30.40	29.08	33.43	30.34
Airport – Gate Area	0.5	30.63	35.07	–	38.72
	2.5	30.28	35.01	–	37.09
	4.5	29.97	35.96	–	38.03
	6.5	16.40	36.85	–	–

5.4 Balloon measurements to domestic buildings (1-6 GHz)

Measurements have been made in the United Kingdom of building entry loss into a number of domestic buildings of traditional construction. These measurements were made at 1.4 GHz, 2.4 GHz and 5.8 GHz, and used a tethered balloon to explore a range of elevation angles.

Details of measurement locations are given in Table 9.

TABLE 9

Building	Date	Measurement locations
Small offices/flats (3 floors)	1985	Measurements in two offices (1st floor)
Detached house (3 floors)	1905	Kitchen (ground) and bedroom (1st floor)
Terraced house (2 floors and attic)	1880	Living room (ground), Bedroom (1st floor) and study (2nd floor)
Terraced house (2 floors)	1965	Dining room & living room (ground), hallway (1st floor)

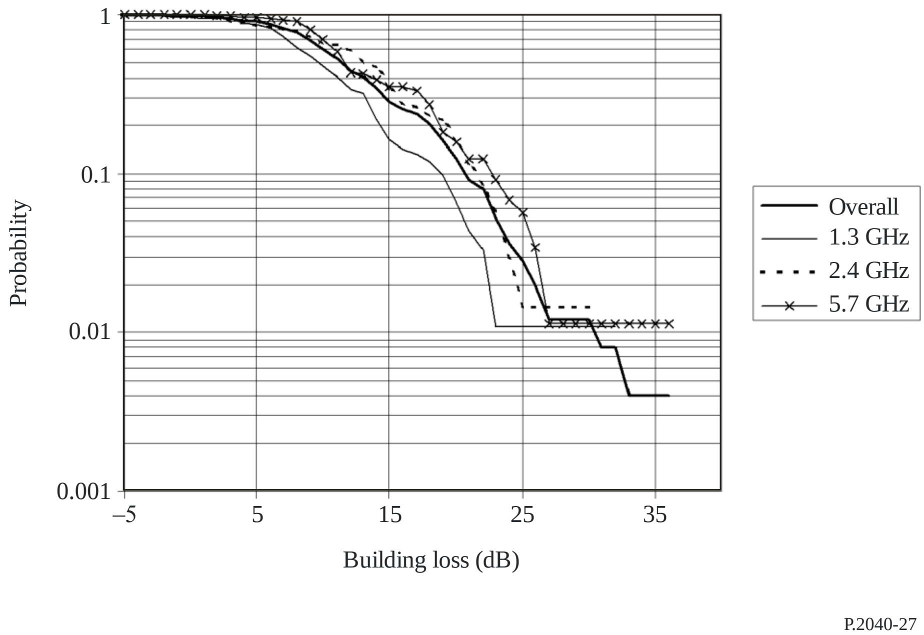
The measurements were made using CW transmitters suspended from a tethered helium balloon, which allowed elevation angles up to around 70º to be explored. The receiver was switched between an indoor measuring antenna and an external reference antenna. The measuring antenna was moved along a 1 m track under computer control, to allow spatial averaging of measurements.

Omnidirectional antennas were used at both transmitter and receiver, and corrections were applied for antenna vertical radiation patterns, and the difference in free-space loss between the reference and measuring antennas.

Following the corrections described above, a data set giving the mean penetration loss for each test location was obtained. The cumulative distribution function (CDF) of these results is shown in Fig. 8, and represents the statistics of mean local loss with respect to all 11 receiver locations, at all elevation angles. The receiver locations were randomly chosen and were almost entirely NLoS to the balloon.

FIGURE 8

Overall statistics of building entry loss

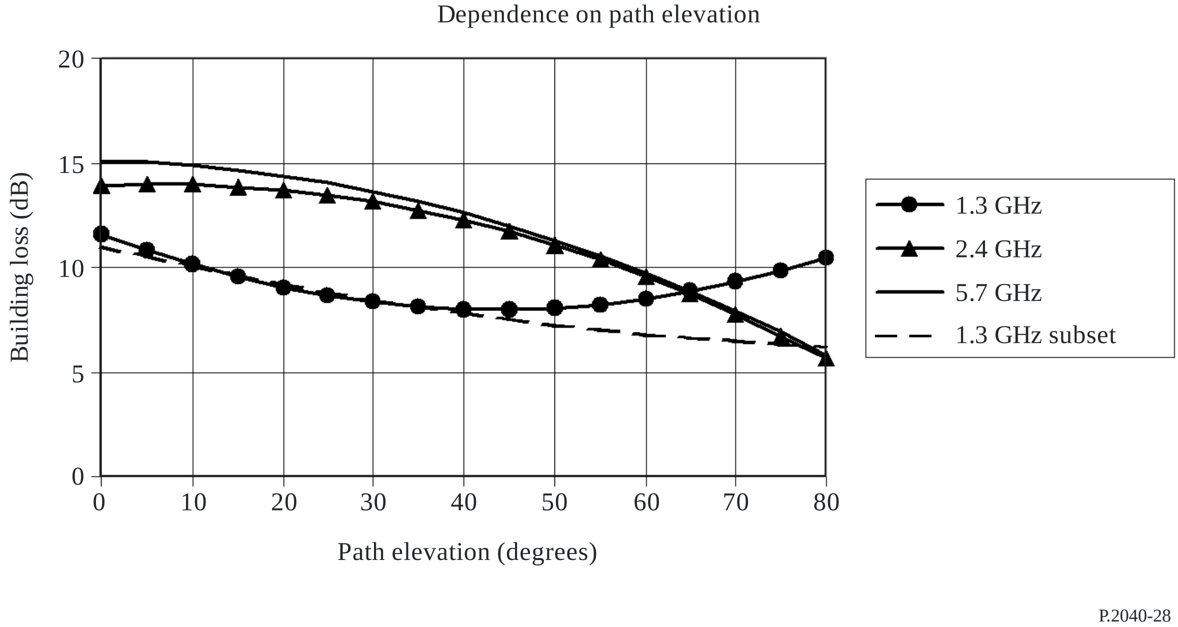


The mean value of building entry loss, at all frequencies, is 11.2 dB. The results shown in Fig. 7 show a slight frequency dependence in the results. Mean values of penetration loss are 9.2 dB at 1.3 GHz, 11.2 dB at 2.4 GHz and 12.7 dB at 5.7 GHz.

Figure 9 shows the elevation dependence of the measurements (polynomial curves fitted to measurement points).

FIGURE 9

Mean values for each frequency compared



The results at 1.3 GHz show an anomalous increase in the penetration loss for higher elevation angles. Examination of the measurement data shows that this effect is due to one set of measurements and the effect of excluding this data is shown in the dotted curve.

It can be seen that, except at the lowest frequency, there is a slight decrease in penetration loss for higher elevation angles. This decrease in building loss with elevation runs counter to the assumptions made in some previous models. It may be that this behaviour is characteristic of domestic buildings, where floors and ceilings are typically of light wooden construction.

Some dependence, of the averaged results, on the building floor is apparent, with the ground floor and first floor results generally showing some 5-8 dB greater loss than those for the second floor. It should be borne in mind, however, that only one set of measurements was made on a second floor, and the location was a converted roof space, used as a home office.

Building shadowing loss measurements

Measurements have been carried out in Australia to determine values of building shadowing loss to be used in planning frequency sharing between the fixed-satellite service and the fixed service.

The building shadowing loss is defined as transmission loss through a building.

The frequency is 11 GHz. Polarization is vertical and horizontal.

Table 10 shows the average results of measurements at 11 GHz through the different types of buildings.

TABLE 10

Mean and standard deviation of loss by polarization and building type

Test site	Avg. loss (V-Pol)	Std. dev.	Avg. loss (H-Pol)	Std. dev.
1 Wooden building (lengthways)	26.4 dB	7.1	–	–
1A Wooden building (widthways)	10.0 dB	7.0	8.3 dB	5.0
2 Concrete/brick building	30.1 dB	5.0	28.6 dB	5.5
3 Metal shed	36.4 dB	4.1	35.0 dB	3.2

The measurements show a high dependence on construction material in determining:

– the primary mode of propagation; and

– the amount of attenuation caused by the obstacle.

Wooden construction materials caused the lowest average attenuation of 10.0 to 25.0 dB, brick and concrete between 25.0 and 35.0 dB and metal between 35.0 and 40.0 dB. The primary mode of propagation for wooden and concrete structures was transmission, while the dominant mode of propagation for metal structures was propagation by diffraction.

During propagation by diffraction, there was a high dependence on diffraction angle. As the diffraction angle increased from the corners (i.e. towards the centre of the building shadow) the amount of attenuation due to diffraction increased (on the order of 5.0 to 10.0 dB).

Although there was dependence on polarization at each measurement point, there was little to no dependence on polarization or path length from the standpoint of averaged data. The average attenuation variation between horizontal and vertical polarizations was less than 1.5 dB.

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6 Impact of thermally-insulating materials

6.1 Introduction

A large body of measured data already exists and this study could add only a small amount to this. The focus was therefore on a careful assessment of the impact of well-characterised changes to building insulation.

A series of measurements have been undertaken on a small detached house; measurements of entry loss were made to the un-modified structure, with metalised windows and when fitted with foil-backed plasterboard. A further set of measurements was also made with window apertures covered in foil, as a diagnostic experiment, and to test the sensitivity to different incidence angles. Measurements were also made in a contrasting building – a much larger Victorian structure (‘The Mansion’).

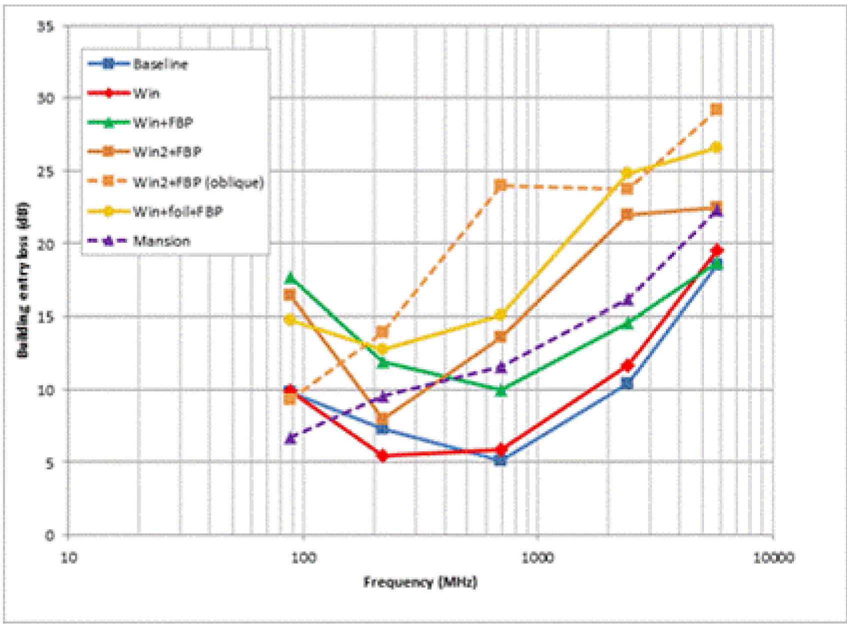
Measurements made at five frequencies: 88 MHz, 217 MHz, 698 MHz, 2 410 MHz and 5 760 MHz; in the trials, a transmitter was carried so as to fully explore each room in a semi-random manner, with received field strength being logged at an outdoor receiver positioned some 30-50 m from the building. Each room in a building was characterised in terms of the median signal level, and this was related to the field immediately outside the building at the same height to determine the building entry loss.

6.2 Median building entry loss

Overall summary results are given in the figure below (in which 'win1' and 'win2' indicates the fitment of different metalised windows and 'FBP' of foil-backed plasterboard). All curves relate to measurements in the small, modern, house except for the single curve identified as 'mansion'.

FIGURE 10

Overall summary building entry loss results



The relatively high losses seen at 88 MHz appear to be an anomalous feature of the small house; the effect was not seen when a path between terminals was more oblique with respect to the front wall of the house (although the results for 698 MHz now seem anomalous, illustrating the complexity of the mechanisms involved).

6.3 Variability of loss within a room

Data has also been gathered on signal variability, which is significantly higher inside buildings due almost entirely to multipath effects. Figure 10 shows time-series[1] of measurements at 88 MHz and 5.7 GHz (bottom), illustrating the variability of signals within one room of the house, compared with the variability measured over an equivalent outdoor area.

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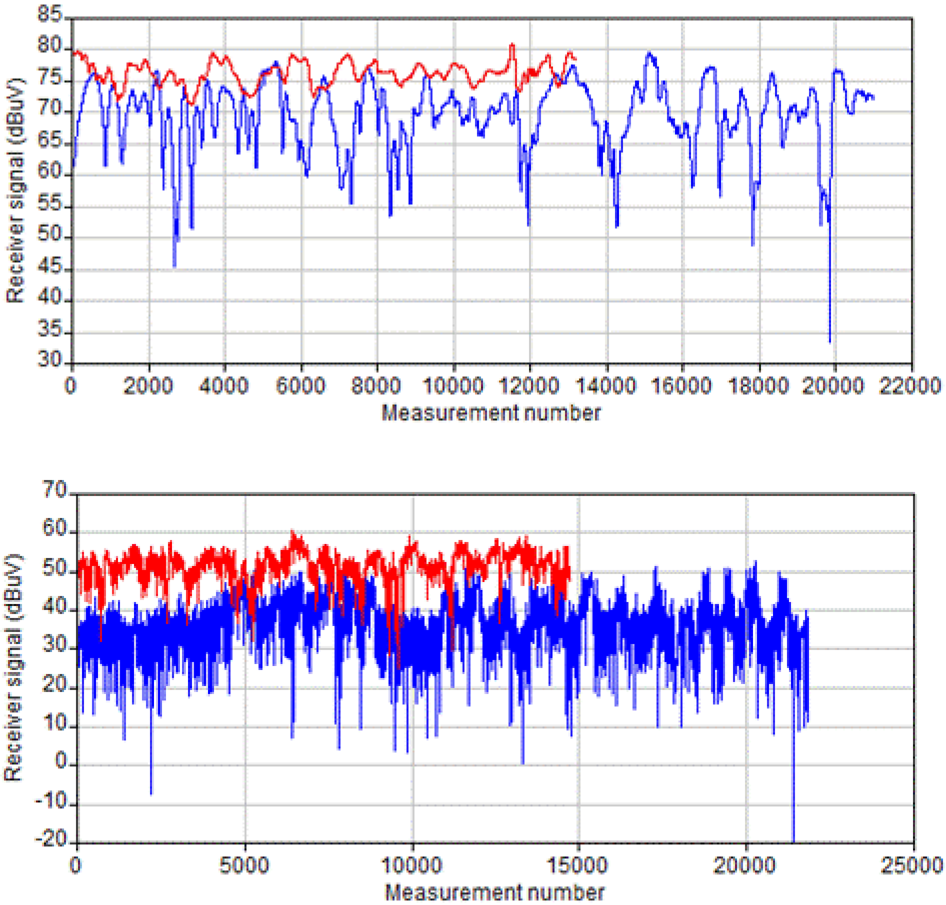
[1] Sampled at equal time-intervals; the faster pace of measurement outdoors resulted in fewer samples being collected.

FIGURE 11

Measurements made indoors (blue) and outdoors (red) – see text



The results at both frequencies show similar trends. The inside signals are weaker on average due to the attenuation of the building. It is also clear that there is more variability on the measurements from inside the building. This is as expected because the inside environment is more rich in multipath than the outside environment. The standard deviations at 88 MHz are 5.5 dB (inside) and 1.8 dB (outside) and at 5.7 GHz are 6.8 dB (inside) and 3.8 dB (outside).

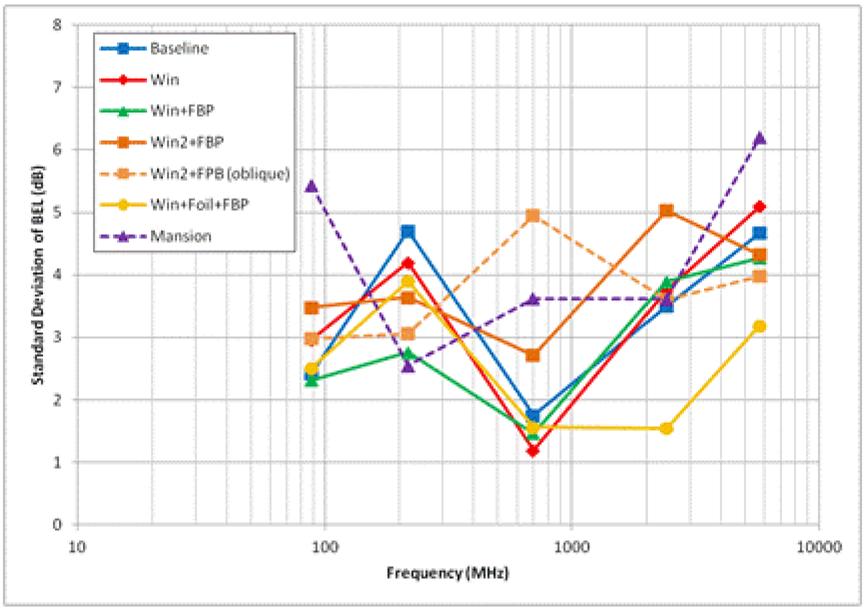
These standard deviations relate mainly to signal variability due to multipath and a small contribution (less than a decibel) due to the path length variation over the measurement area.

6.4 Variability of loss from room-to-room

The standard deviation of the room median building entry loss values are shown in Fig. 12 for the different building configurations. There is no very useful frequency trend. The results for the small house configurations are reasonably consistent for type 1 glass, with type 2 glass and the artificial foil-over-windows cases showing some differences. The standard deviation is generally higher in the mansion.

FIGURE 12

Room to room standard deviation of building entry loss



The room-to-room standard deviations are about half the values obtained for the signal variability within the living room alone. This is as expected because multipath has been removed in the room-to-room calculation. However the significant difference between the two buildings suggests that a good measure of 'variability' really needs to take account of a larger population of building types.

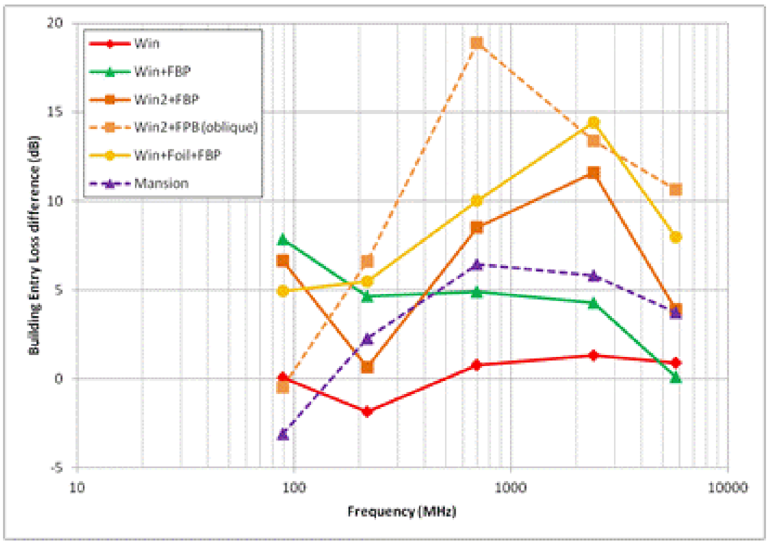
It is not clear that any adequate model yet exists to characterise this variability.

6.5 Impact of insulating materials on loss

The measurements show increasing levels of building entry loss as modern insulating materials are added to an uninsulated house (see Fig. 13).

FIGURE 13

Increase in BEL compared to baseline configuration



For a small house, a combination of foil-backed insulation and metalised double glazed windows (representative of a well-insulated property), added 5-10 dB to the building entry loss. The losses increase with frequency, but most of the increase is accounted for in the uninsulated configuration and the additional loss due to the insulating materials shows relatively weak frequency dependence. An additional 5 dB of screening was obtained when, in addition, all windows and door apertures were covered by foil; this might approximate to a ‘worst case’ whole building figure for building entry loss.

7 Measurements at 3.5 GHz

7.1 Environment

Concrete and glass are two typical materials for the building.

In this contribution, these two materials are measured.

For the concrete material, 50 cm width * 100 cm length * 10 cm thickness concrete slab is tested. The test environment is an anechoic chamber in Tsinghua University, Beijing, China.

For the class material, the measurement field was located at the FIT building, Tsinghua University in Beijing, China. The FIT building is a typical office building full of coated glass, the overall window to wall ratio is more than 2:1. The building height is about 20 m. Coated glass offers enhanced benefits to buildings, partitions, skylights, curtain walls, and other applications. Annex 2 also provides similar material’s building entry loss results.

The characteristics of the environment scenario are shown in Tables 11 and 12.

TABLE 11

Environment characteristics for the concrete scenario

Characteristics	
Location	Anechoic chamber in Tsinghua University
Building type	Basement room
Object of the measurement	Normal concrete slab
Thickness of the concrete slab	10 cm and 20 cm

The measurement object is the concrete slab in the middle of the transmitter and receiver antenna. The thickness is about 10 cm.

TABLE 12

Environment characteristics for the glass scenario

Characteristics	
Location	FIT building East hall, Tsinghua University, Beijing, China
Building type	Office
Object of the measurement	The coated glass between the FIT building hall and the centre garden
Thickness of the glass	Total 10 mm (two 2 mm glass plus 6 mm inner gap)
Height of buildings	About 20 m
Surrounding	Typical office building which full of glass, window-to-wall ratio is more than 2:1.

The measurement object is the glass between the FIT building hall and the centre garden. The glass is typical large two layer class in which the total thickness is about 10 mm including the inner gap. Note that 7 cm width metal pillars connect adjacent glass panels.

7.2 Measurement configuration

The measurement configuration parameters are shown in Table 13.

TABLE 13

Measurement configurations

Characteristics	
Centre frequency	3.34-3.66 GHz, granularity is 0.02 GHz
Bandwidth range	Total 300 MHz
Tx height for concrete scenario	43 cm above the ground, the ground height is 0 m
Rx height for concrete scenario	43 cm above the floor height, the floor height is 13.5 mm
Tx height for glass scenario	161 cm above the ground, the ground height is 0 cm
Rx height for glass scenario	147.5 cm above the floor height, the floor height is 13.5 cm

The Agilent E4438C ESG vector single generator operates at 3.34-3.66 GHz was applied to generate the transmit signal. The ROHDE&SCHWARZ spectrum analyser is used to conduct the building entry loss measurement. Incident angle is 0°.

7.3 Measurement results at 3.5 GHz

The measurement results are shown in Table 14.

TABLE 14

Loss due to coated glass and concrete slab at 0 incident angles

Frequency	**Concrete slab (10 cm thickness)**		**Concrete slab (20 cm thickness)**		**Coated glass office (10 mm thickness)**	
	Mean (dB)	Standard deviation (dB)	Mean (dB)	Standard deviation (dB)	Mean (dB)	Standard deviation (dB)
3.5 GHz	16	2.5	20	1.5	25	4

8 Measurements in Stockholm at 0.5 to 5 GHz

8.1 Configuration of the set-up

Figure 14 shows a map of the measurement area. The transmitter location is indicated with a circle on building 11. The outdoor measurement areas at buildings 27, 37 and 81 are marked with ellipses.

FIGURE 14

Map of the measurement area

Four separate CW (continuous wave) transmitters were used to transmit at $f_1 = 460$ MHz, $f_2 = 881$ MHz, $f_3 = 1\,859$ MHz and $f_4 = 5.11$ GHz from a roof of a 29 metres tall building in an urban environment (Figs 1 and 2). This location was a few meters above the rooftops of the surrounding buildings (the transmitter location was on the roof of 30 m tall building and the surrounding buildings era around 25 m tall). The transmit power was between 23 dBm and 28 dBm. Vertical halfwave dipole antennas were used both at the receiver and the transmitter ensuring equal antenna pattern at all frequencies. A vector network analyser (VNA) was used to sample the receive signal at the different frequencies. In order to improve the sensitivity of the receiver a wideband LNA was used. Applying Doppler filtering in addition, based on 201 time samples taken at each frequency, made possible to measure path loss higher than 130 dB at all frequencies. The measurement routes covered corridors and other open areas.

8.2 General results

The cumulative distribution functions of excess path loss in all buildings are shown in Fig. 15 for the different frequencies. It is striking how small the general frequency dependency is in the band between 460-1 860 MHz. The mean is around 30 dB and the corresponding standard deviation is about 8 dB. In the band 1.8-5.1 GHz, however, the median excess loss increases more than 5 dB with frequency. This increase may partly be explained by shielding due to metallic window coating which attenuates the received signal substantially more at 5.1 GHz than at the other frequencies. This effect was indeed confirmed for building 27 by measuring the excess loss immediately behind the exterior wall facing the transmitter in line of sight (LoS) conditions. The resulting shielding loss of the exterior wall is 12, 16, 16 and 22 dB at carrier frequencies 460, 880, 1 860 and 5 100 MHz respectively. Buildings 11 and 32 also show an increase of excess loss at 5 GHz though the windows are not coated (as shown in Fig. 16). These buildings were located at short distance from the transmitter suggesting a corresponding enhancement of some frequency dependent propagation mechanisms. It was indeed possible to explain the frequency dependency as a diffraction effect in building 11.

FIGURE 15

Cumulative distribution functions of the excess path loss in all buildings

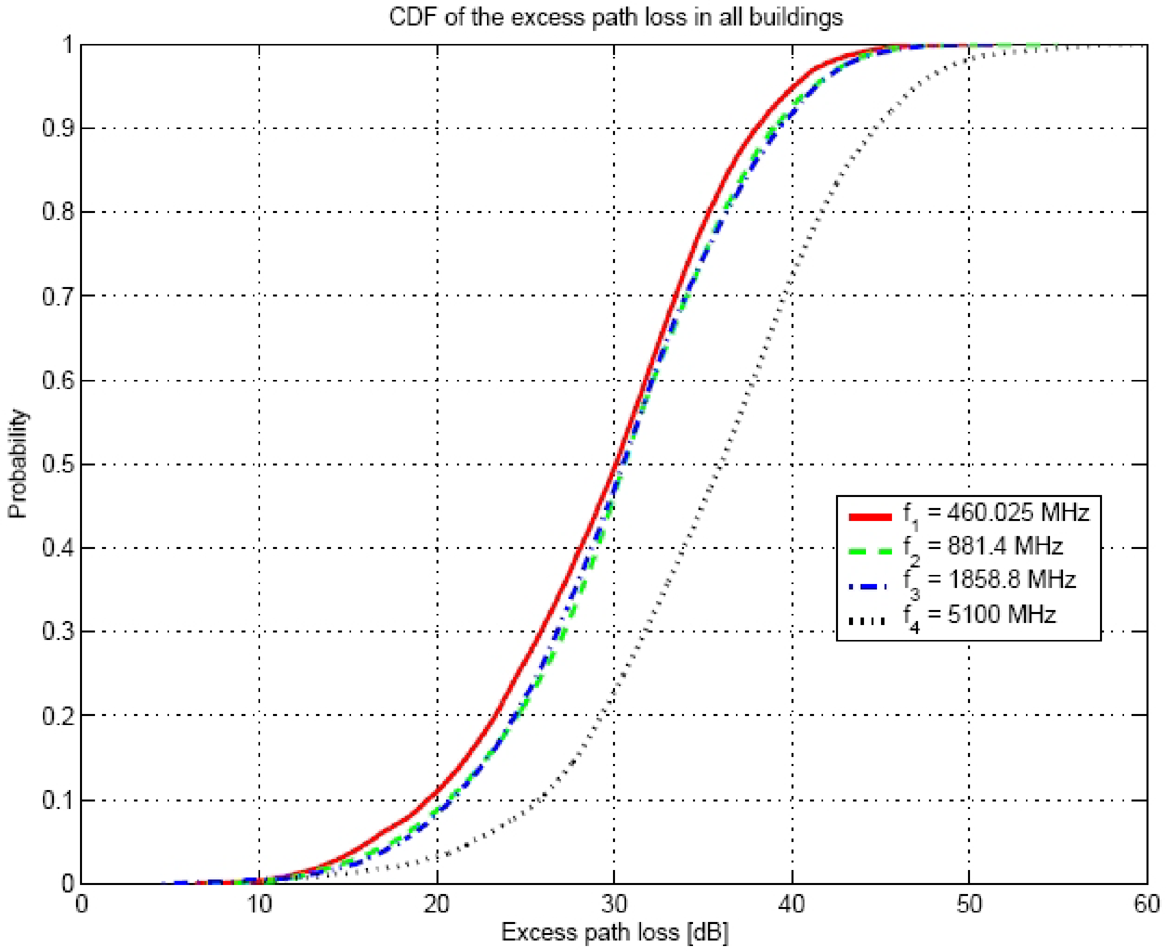
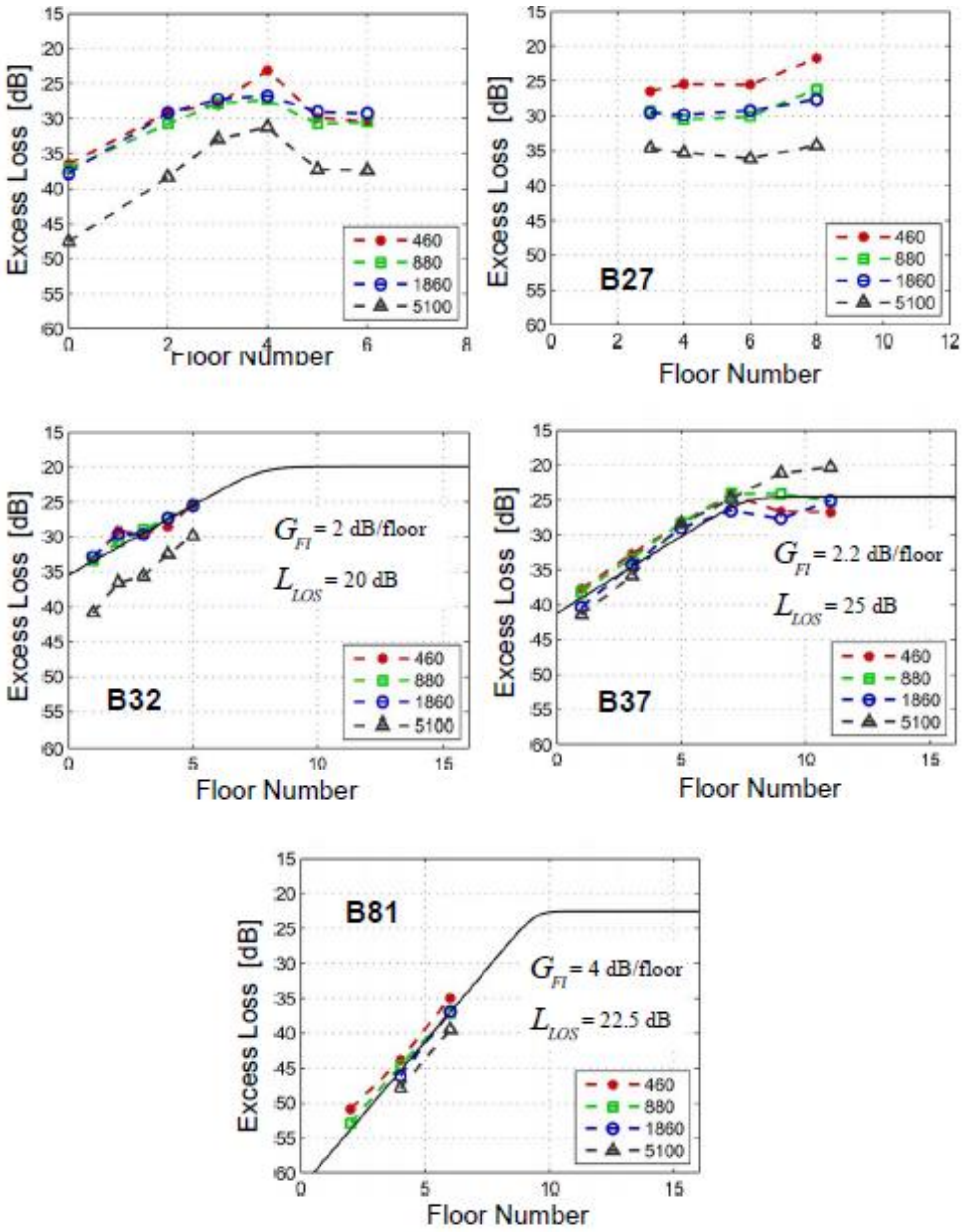


FIGURE 16

Mean excess path loss plotted against floor number for the different carrier frequencies in buildings 11, 27, 32, 37 and 81



For further details refer to J. Medbo *et al.*, "Multi-Frequency Path Loss in an Outdoor to Indoor Macrocellular Scenario", EuCAP 2009, Berlin, Germany[2].

8.3 Average excess loss results

Building entry loss can be evaluated using two methods:

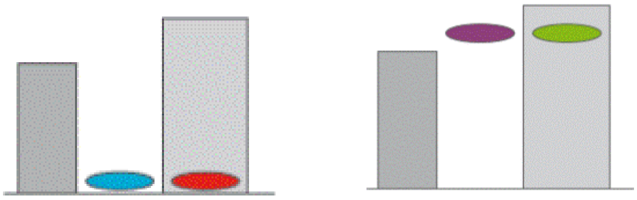
Method 1: Loss difference indoors and outdoors at ground level: $L_{out} - L_{in}$

Method 2: Excess loss at floor levels where building is LoS: $L_{FS} - L_{in}$

[2] Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5068371.

FIGURE 17

Methods for evaluation of building entry loss (left = method 1, right = method 2)



Penetration loss data for LoS conditions is not available in many cases since the buildings do not reach LoS height. For such buildings (e.g. building 81), L_{LoS} may be taken as the difference L_{Diff} between measured loss outdoors and indoors at ground level. This was done for buildings 27, 37 and 81 (see Table 15). For buildings 27 and 37 it is possible to compare the two methods. It turns out that L_{Diff} underestimates L_{LoS} in these two cases. The underestimation may be explained by the fact that the outdoor loss measurements were restricted to areas around the buildings which were not facing the transmitter (see Fig. 15) and thus giving higher loss. Since L_{LoS} is not known for building 81 the best one can do is assume $L_{LoS} = L_{Diff}$. The resulting floor number where LoS occurs, n_{Flb}, is around 9 which is consistent with visual inspection done at the transmitter location. The present results indicate that the two methods to determine the building entry loss give similar results. The outdoor measurement method is however uncertain due to large variations in shadowing suggesting the use of L_{LoS} whenever possible.

TABLE 15

Estimates of L_{LoS}

Building	Frequency (MHz)	Loss – Ground floor (dB)	Loss – Outdoors (dB)	Loss difference (dB)
81	460	48	27	21
	880	48	28	20
	1 860	51	26	25
	5 100	–	25	–
37	460	38	16	22
	880	38	21	17
	1 860	40	21	19
	5 100	41	22	20
27	460	26	3	23
	880	29	8	21
	1 860	30	8	22
	5 100	35	7	28

8.4 Method 1 versus Method 2 results

Method 2 gives typically 0-10 dB higher penetration loss.

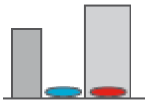
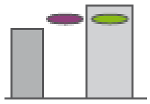
There is one dominating direction in LoS conditions due to the angle-dependent penetration loss.

There is multipath in N_{LoS} conditions; often paths with perpendicular incidence.

Method 1 is not reliable if the outdoor area does not have uniform propagation conditions, e.g. partial LoS.

TABLE 16

Comparison of loss estimates

Building	**Frequency (MHz)**	**Penetration loss Method 1 (dB)** 	**Penetration loss Method 2 (dB)** 	**Diff**
37	460	**22**	**27**	**5**
	880	**17**	**27**	**10**
	1 860	**19**	**25**	**6**
	5 100	**20**	**20**	**0**
27	460	**23**	**25**	**2**
	880	**21**	**30**	**9**
	1 860	**22**	**30**	**8**
	5 100	**28**	**35**	**7**

9 Building entry loss measurement at 3.5 GHz in Beijing

9.1 Measurement scenarios

Three typical office buildings in China are measured, named as building A, building B and building C, which have different structure and material. Building A is with reinforced concrete shear wall and one-way transparent glass which is with a thin metal coating. The thickness of the bearing wall is 35 cm ~ 38 cm. In addition, the building's exterior wall is being equipped with thermal insulation material whose structure is the foam polyethylene sheet and metal reflective layer. Building B is a modern building combined the toughened glass with the reinforced concrete. The toughened glass is laid in the wall which is known as a common toughened glass without metal coat. Building C is with reinforced concrete shear wall structure and one-way transparent glass.

9.1.1 Building A

Building A is with reinforced concrete shear wall structure, which has exterior load-bearing walls and some interior load-bearing walls. The thickness of the bearing walls is 35 cm ~ 38 cm. The glass of windows of the building is known as one-way transparent glass which has a good visibility from the inside to outside but a poor visibility from the outside to inside. This one-way transparent glass is with a thin metal coating, so it will reflect the electromagnetic wave and bring big penetration loss. In addition, the building’s exterior wall is being equipped with thermal insulation material whose structure is the foam polyethylene sheet and metal reflective layer.

The receiving antenna is on an outdoor platform which is on 4th floor. The pictures are shown in Fig. 18. Only two operators are on the platform during the test, and they stay away from the receiving antenna. The height of the transmitting antenna is 2.3 m, and the height of the receiving antenna is 1.5 m.

The receiving point located on the 4th floor platform outdoor, the main receiving point is labelled as R1, marked as blue point in Fig. 19. Some transmitting points on the 4th floor indoor are marked as red points in Fig. 19. Other transmitting points on the 5th floor indoor are marked as red points shown in Fig. 20. Furthermore the receiving points and transmitting points are marked with coordinate values, R1 is the coordinate origin.

FIGURE 18

The outdoor platform of the building A: The building scene from the receiving point, the thermal insulation layer is adding to the exterior wall of the building A (Panoramic camera model, Middle image of the building is slightly bent)

FIGURE 19

The transmitting points indoor and the receiving points outdoor on the 4th floor, the length of the platform is 28 m

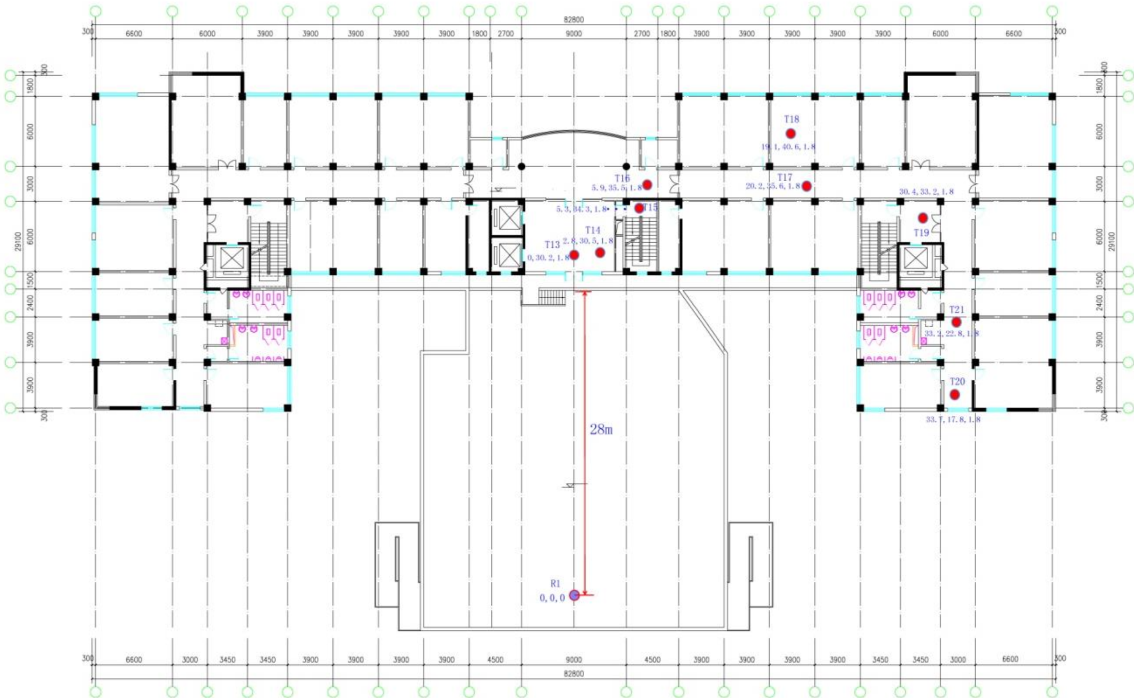
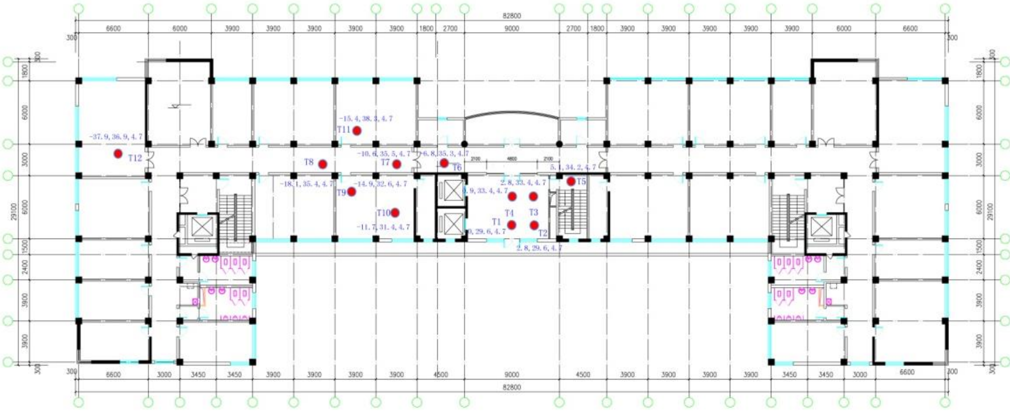


FIGURE 20

The transmitting points indoor on the 5th floor



The coordinates of the receiving points and transmitting points in building A are shown in Table 17.

TABLE 17

The coordinates of the receiving points and transmitting points in building A (unit: m)

Points	x	y	z
R1	0	0	0
T1	0	29.6	4.7
T2	2.8	29.6	4.7
T3	2.8	33.4	4.7
T4	0.9	33.4	4.7
T5	5.1	34.2	4.7
T6	–6.8	35.3	4.7
T7	–10.6	35.5	4.7
T8	–18.1	35.4	4.7
T9	–14.9	32.6	4.7
T10	–11.7	31.4	4.7
T11	–15.4	38.3	4.7
T12	–37.9	36.9	4.7
T13	0	30.2	1.8
T14	2.8	30.5	1.8
T15	5.3	34.3	1.8
T16	5.9	35.5	1.8
T17	20.2	35.6	1.8
T18	19.1	40.6	1.8
T19	30.4	33.2	1.8
T20	33.7	17.8	1.8
T21	33.2	22.8	1.8

Some typical transmitting points' pictures in building A are shown in Figs 21-23.

FIGURE 21

The transmitting point in the corridor of the building A

FIGURE 22

The transmitting point by the glass door of the building A

FIGURE 23

The transmitting point in the stair channel of the building A

9.1.2 Building B

Building B is a modern building combining toughened glass with reinforced concrete. The toughened glass is laid in the wall which is known as a common toughened glass without metal coat. Part of exterior wall is equipped with a brown ceramic tile. There is a parking lot outside the building, the length of which is about 35 m. In order to avoid the influence of vehicle movement, the method is:

– The test is taken at the weekend to make sure there are few vehicles and staff.

– Make sure the receiving antenna is away from the vehicle.

– The height of the receiving antenna is set to 2.3 m to ensure that the connection between the transmitting antenna and the receiving antenna is not blocked by vehicles.

The main receiving point is R3, which is marked with blue point in Fig. 24, and the transmitting points on the 1st floor are marked with red points in Fig. 25. The transmitting points on the 2nd floor are marked with red points in Fig. 26. The transmitting points on the 3rd floor are marked with red points in Fig. 27. The height of the transmitting antenna is 2.3 m and the height of the receiving antenna is 2.3 m from the floors at that time.

FIGURE 24

Parking lot outside the building B: The building scene from the receiving point

FIGURE 25

The transmitting points indoor and the receiving point outdoor on the 1st floor in building B, the length of the outdoor parking lot is 35 m

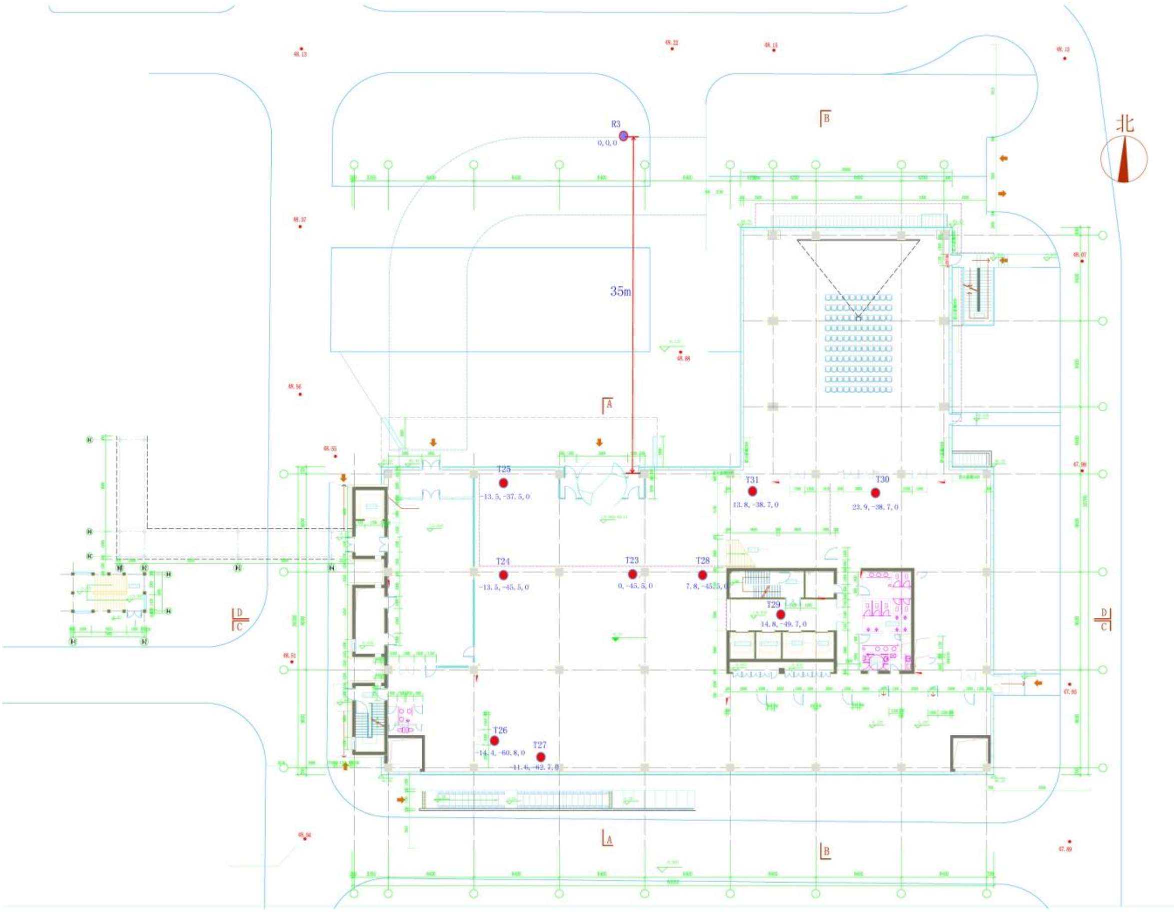


FIGURE 26

The transmitting points on the 2nd floor in building B

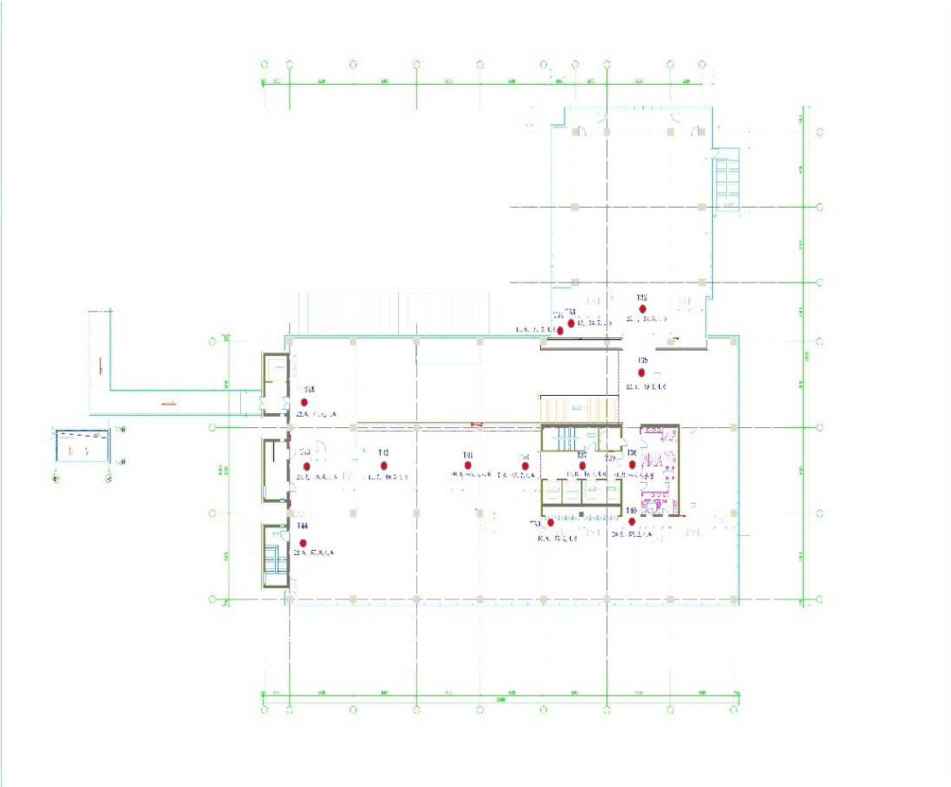
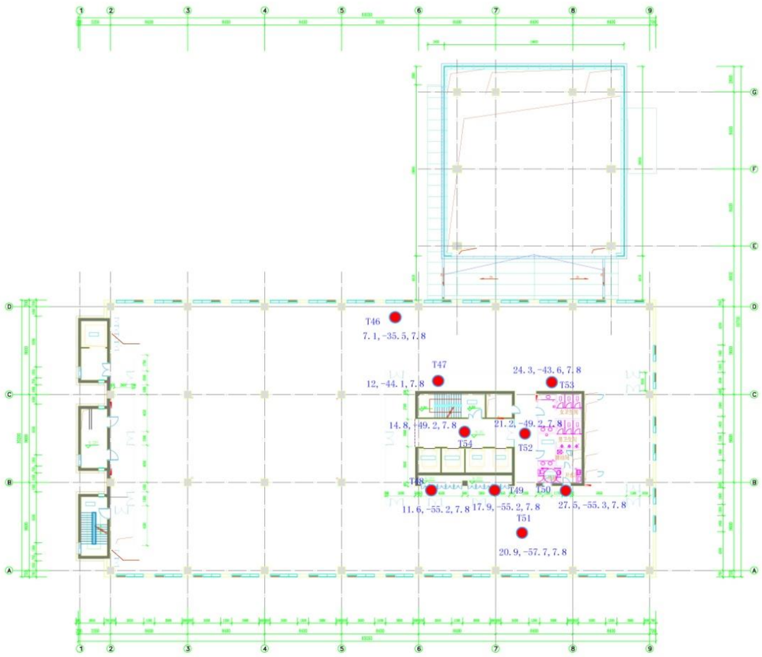


FIGURE 27

The transmitting points on the 3rd floor in building B



A coordinate system is formed with the R3 being a coordinate origin. The coordinates of the transmitting points and receiving point are shown in Table 18.

TABLE 18

The coordinates of the receiving points and transmitting points in building B (unit: m)

Points	***x***	***y***	***z***
R3	0.0	0.0	0.0
T23	0.0	–45.5	0.0
T24	–13.5	–45.5	0.0
T25	–13.5	–37.5	0.0
T26	–14.4	–60.8	0.0
T27	–11.6	–62.7	0.0
T28	7.8	–45.5	0.0
T29	14.8	–49.7	0.0
T30	23.9	–38.7	0.0
T31	13.8	–38.7	0.0
T32	22.1	–31.3	4.6
T33	13.0	–34.7	4.6
T34	11.9	–34.5	4.6
T35	22.1	–39.8	4.6
T36	21.2	–49.2	4.6
T37	14.8	–49.7	4.6
T38	7.8	–49.7	4.6
T39	10.9	–55.2	4.6
T40	20.8	–55.2	4.6
T41	–0.1	–49.5	4.6
T42	–11.7	–49.5	4.6
T43	–21.5	–49.5	4.6
T44	–22.6	–57.8	4.6
T45	–22.6	–41.6	4.6
T46	7.1	–35.5	7.8
T47	12.0	–44.1	7.8
T48	11.6	–55.2	7.8
T49	17.9	–55.2	7.8
T50	27.5	–55.3	7.8
T51	20.9	–57.0	7.8
T52	21.2	–49.2	7.8
T53	24.3	–43.6	7.8
T54	14.8	–49.2	7.8

Some typical transmitting points pictures in building B are shown in Figs 28-29.

FIGURE 28

The transmitting point in the lobby on the 1st floor in building B
(in transmitting point the receiving point can be seen through glass)

FIGURE 29

The transmitting point next to the elevator on the 2nd floor in building B

9.1.3 Building C

Building C is with reinforced concrete shear wall structure. The glass of windows of the building is known as one-way transparent glass which has a good visibility from the inside to outside but a poor visibility from the outside to the inside. In the measurement only one transmitting location is selected, and the location is near the window, and 3 receiving locations are selected. From the outdoor level, the transmitting antenna height is 3.3 m, the receiving antenna height is 2.3 m, the horizontal distance from receiving point outdoor to transmitting point indoor is 9.65 m, 17.65 m and 29.65 m.

9.2 Test methodology

In building A and B, 11 frequency points are selected in 3.4 GHz to 3.6 GHz frequency band during the test, which are: 3 401 MHz, 3 421 MHz, 3 441 MHz, 3 461 MHz, 3 481 MHz, 3 501 MHz, 3 521 MHz, 3 541 MHz, 3 561 MHz, 3 581 MHz, 3 601 MHz.

In building C, 3 frequency points are selected: 3 401 MHz, 3 501 MHz, 3 599 MHz.

9.2.1 Measuring system and instrument

The devices of measuring system are shown in Table 19.

TABLE 19

The antenna selection consideration

Transmitting antenna	Omni-directional vertical polarization antenna
Receiving antenna	• In building A and B: Omni-directional vertical polarization antenna. • In building C: horn antenna with vertical polarization
Transmitter	Agilent E8267D signal generator
RF power amplifier	The output power in the test is set to 33 dBm
Receiver	Agilent N9030A signal analyzer

We have developed an automatic program in order to control instruments and record test data by LAN. In each location and frequency points, 500 continuous reading are obtained which will cost about 8 ~10 seconds.

9.2.2 Calculation method of building entry loss

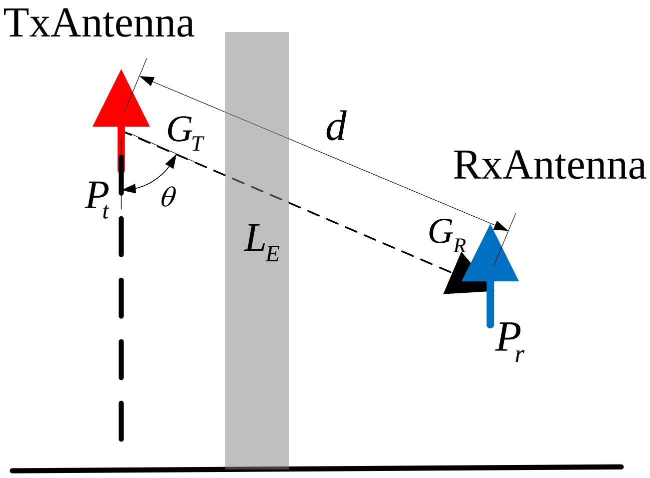
The free space loss can be calculated as:

$$L_f = 32.45 + 20 \lg d_{(m)} + 20 \lg f_{(GHz)} \quad (3)$$

where *d* is defined in Fig. 30. *f* is carrier frequency (GHz). Set transmitted power be P_t (dBm) and received power be P_r (dBm), the building entry loss is expressed as L_E, transmitting antenna gain and receiving antenna gain in transmission path are expressed as G_t and G_r, relatively.

FIGURE 30

The location relationship between the receiving antenna and the transmitting antenna



Then we can get equation (4).

$$P_{t(dBm)} + \left(G_t - L_f - L_E + G_r\right) = P_{r(dBm)} \tag{4}$$

And then the entry loss can be deduced from equation (5).

$$L_E = \left(P_{t(dBm)} - P_{r(dBm)}\right) - L_f + (G_t + G_r) \tag{5}$$

The omni-directional antenna used in the test is similar to half wave dipole antenna whose gain is 2.15 dB, and the normalized directivity function of electric field of half-wave dipole antenna is expressed as equation (6).

$$F(\theta) = sin\theta \tag{6}$$

Where θ is defined in Fig. 29. From equation (6) we can get equation (7).

$$G_t + G_r = 4.3 + 10\,\mathrm{lg}([F(\theta)]^4) = 4.3 + 10\,\mathrm{lg}(\sin^4\theta) \tag{7}$$

In the scenario of building C, for horn antenna is used as receiving antenna, so the receiving antenna gain is properly considered in calculation.

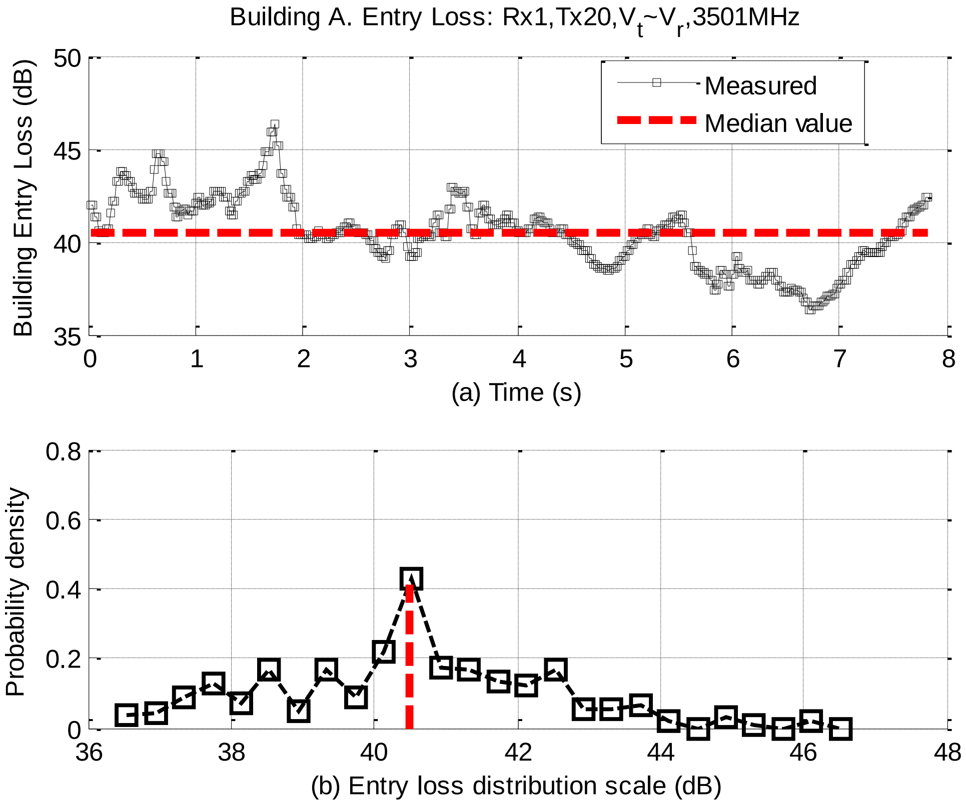
9.3 Measurement results

9.3.1 Measurement results and analysis of building A scenario

After processing the original test data the entry loss of building A can be obtained. Figure 31 shows an example of curve of readings in time domain and median value.

FIGURE 31

Measurement of building entry loss: readings in time domain and median value



The median values of building entry loss measured above are shown in Table 20. The categories of all links from transmitters and receivers can be separated as four types:

– Category0: Outer-wall with one-way transparent glass

– Category1: Outer-wall+1 inner-wall

– Category2: Outer-wall+2 inner-wall

– Category3: Outer-wall+ elevator.

TABLE 20

The median value of entry loss (building A, unit: dB)

Frequency (MHz)	3 401	3 421	3 441	3 461	3 481	3 501	3 521	3 541	3 561	3 581	3 601	Category
Tx 1	27.3	20.2	36.9	29.5	28.7	32.1	37.7	24.5	28.4	45.0	38.5	0
Tx 2	20.0	19.5	19.7	19.9	22.1	29.1	16.1	20.7	18.1	17.6	28.0	0
Tx 3	21.2	25.8	22.3	21.1	25.0	22.9	27.4	25.1	23.8	23.4	28.1	0
Tx 4	34.3	26.7	24.4	25.7	23.1	26.8	25.9	27.6	22.0	24.0	27.4	0
Tx 5	46.3	45.1	56.5	41.4	40.3	44.2	45.1	36.6	37.9	41.3	42.9	1
Tx 6	44.5	40.6	38.3	42.0	43.0	37.7	43.2	41.2	47.0	49.7	56.6	3
Tx 7	42.6	44.4	49.2	44.7	71.3	44.1	41.0	44.2	42.7	39.9	39.0	3
Tx 8	39.1	45.8	45.7	42.8	43.3	46.5	48.0	49.0	51.4	53.6	53.0	1
Tx 9	27.6	36.1	26.5	21.8	36.7	37.2	20.1	31.8	32.9	24.1	31.8	0
Tx 10	19.2	24.8	27.4	25.8	26.1	42.1	30.2	26.9	23.0	24.2	29.8	0

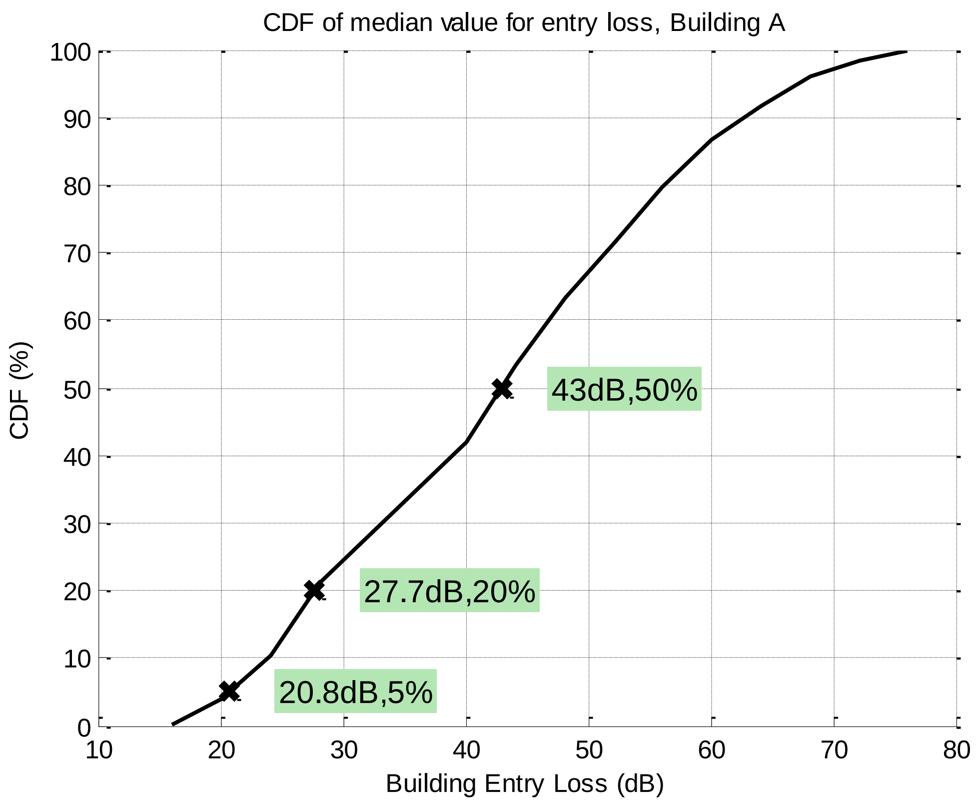
TABLE 20 (*end*)

Frequency (MHz)	**3 401**	**3 421**	**3 441**	**3 461**	**3 481**	**3 501**	**3 521**	**3 541**	**3 561**	**3 581**	**3 601**	**Category**
Tx 11	51.9	57.7	65.4	60.2	53.0	64.3	62.9	63.9	59.7	56.3	51.9	2
Tx 12	60.3	53.6	63.0	56.2	54.1	51.1	51.1	55.1	55.4	57.4	58.4	2
Tx 13	27.1	34.5	33.3	34.9	50.2	28.7	29.0	36.7	32.1	39.2	40.9	0
Tx 14	40.2	35.7	38.1	30.2	26.4	32.4	28.1	33.3	35.4	40.9	30.1	0
Tx 15	53.0	50.7	55.5	49.1	41.6	44.3	57.5	46.7	66.3	56.6	53.1	3
Tx 16	50.5	53.1	60.3	55.6	46.9	50.8	47.2	52.5	57.0	69.0	57.1	2
Tx 17	51.9	52.1	55.5	61.1	44.1	52.7	43.5	50.0	42.1	46.3	49.8	2
Tx 18	60.0	66.2	76.1	68.9	66.8	75.0	69.9	74.0	65.8	70.6	61.7	2
Tx 19	58.3	63.5	64.2	58.3	65.0	66.5	73.2	61.5	60.9	64.1	64.6	2
Tx 20	31.8	33.7	33.7	33.4	32.5	40.5	45.3	43.4	35.3	36.9	33.7	1
Tx 21	43.3	54.5	52.8	50.9	55.2	47.9	59.9	52.6	44.2	50.8	43.2	1

Through analysis of median values of building entry loss (data in Table 20) at each frequency on each transmitter, we can get the CDF, as shown in Fig. 32. And, the mean of data in Table 18 is 42.8 dB and standard deviation is 14.3 dB.

FIGURE 32

Cumulative distribution function of median values of each Tx at each frequency



9.3.2 Measurement results and analysis of building B scenario

After processing the original test data the entry loss of building B can be obtained. The median value of the entry loss measurement above is shown in Table 21. The categories of all links from transmitters to receivers can be separated as four types:

– Category0: Outer-wall with glass

– Category1: Outer-wall+1 inner-wall

– Category2: Outer-wall+2 inner-wall

– Category1: Outer-wall+ elevator.

TABLE 21

The median value of the entry loss (building B, unit: dB)

Frequency (MHz)	3 401	3 421	3 441	3 461	3 481	3 501	3 521	3 541	3 561	3 581	3 601	Category
Tx 23	16.9	8.1	9.6	4.1	9.6	13.5	11.5	5.9	12.6	12.5	18.5	0
Tx 24	22.0	12.6	8.2	15.9	21.0	20.3	13.0	15.0	13.0	22.6	19.4	0
Tx 25	16.1	10.5	21.0	10.5	12.7	13.0	26.6	9.4	21.8	18.8	13.2	0
Tx 26	9.6	12.7	11.2	12.1	22.1	10.8	11.4	14.2	16.0	16.4	6.6	0
Tx 27	16.6	19.5	15.8	23.7	36.7	22.0	14.5	18.9	15.3	16.5	12.0	0
Tx 28	11.3	19.6	10.8	12.2	20.8	21.8	22.9	11.7	19.3	12.2	8.3	0
Tx 29	25.9	22.3	31.9	26.6	29.7	25.1	33.5	22.6	22.0	21.6	24.4	3
Tx 30	20.9	18.3	25.1	18.2	20.4	19.5	19.2	20.5	22.9	32.0	24.7	1
Tx 31	20.4	15.7	12.9	17.8	25.4	13.3	30.7	14.5	20.3	24.6	17.5	0
Tx 32	41.7	36.2	38.4	29.9	47.2	38.2	40.5	38.9	36.2	40.3	35.3	0
Tx 33	36.1	31.3	36.1	22.0	33.6	42.1	38.8	33.4	26.4	26.9	29.4	0
Tx 34	19.9	25.6	31.5	33.5	24.6	23.8	27.4	26.8	36.6	30.7	26.0	0
Tx 35	22.7	27.8	24.4	26.3	34.1	29.1	28.7	21.7	21.3	25.2	24.9	1
Tx 36	40.9	42.3	33.6	45.3	32.0	33.1	41.3	37.8	33.1	47.8	32.5	2
Tx 37	30.1	48.4	46.6	35.1	38.4	40.4	40.0	32.7	41.7	39.1	31.6	2
Tx 38	22.7	17.6	25.3	20.4	16.0	30.1	21.1	24.8	17.7	25.6	20.9	0
Tx 39	34.9	39.7	36.5	31.5	34.0	37.4	36.6	32.0	37.3	34.5	36.3	3
Tx 40	45.3	38.6	35.0	37.5	48.4	43.7	39.2	44.3	39.2	40.9	42.5	3
Tx 41	14.4	21.4	17.8	17.6	20.4	22.2	22.6	16.1	22.8	21.3	26.1	0
Tx 42	18.3	19.4	18.7	16.4	21.6	20.0	33.1	25.8	19.4	23.4	21.8	0
Tx 43	32.9	33.3	30.4	36.5	42.6	30.6	37.9	34.3	32.5	36.3	39.2	1
Tx 44	48.1	35.6	39.1	53.6	43.8	37.0	48.5	42.8	53.8	41.5	35.2	2
Tx 45	30.7	35.9	32.4	47.1	33.7	38.0	31.6	37.6	26.7	36.8	29.6	1
Tx 46	13.4	16.3	32.5	17.2	25.6	19.5	17.4	23.7	20.5	33.4	22.5	0
Tx 47	26.2	29.5	34.8	33.4	37.0	31.9	30.8	47.7	25.4	29.2	35.3	1
Tx 48	39.4	53.2	49.3	43.5	50.6	44.1	48.1	51.2	53.8	48.3	63.0	3
Tx 49	61.2	48.4	60.8	46.1	56.0	57.8	63.2	57.1	57.8	51.0	60.8	3
Tx 50	55.4	58.9	61.1	52.9	52.5	59.7	55.0	53.2	63.7	59.8	51.1	3

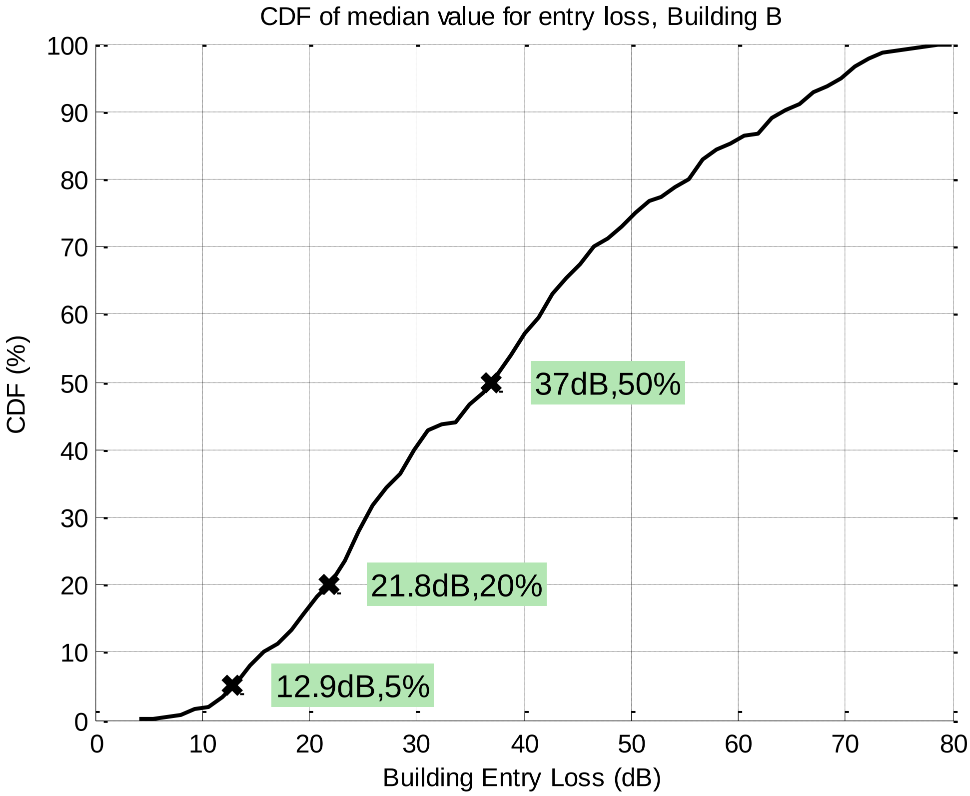
TABLE 21 (*end*)

Frequency (MHz)	**3 401**	**3 421**	**3 441**	**3 461**	**3 481**	**3 501**	**3 521**	**3 541**	**3 561**	**3 581**	**3 601**	**Category**
Tx 51	72.9	64.2	79.9	56.9	58.8	69.5	68.8	64.4	57.9	60.4	59.9	3
Tx 52	49.2	63.1	49.3	57.5	60.9	49.0	60.0	59.3	50.2	55.6	62.9	2
Tx 53	41.5	43.8	42.4	44.5	57.8	46.7	42.4	43.7	35.7	47.7	45.8	2
Tx 54	58.0	70.4	45.5	50.9	53.6	48.0	55.4	48.2	50.2	53.3	56.9	2

Through analysis of median values of building entry loss (data in Table 21) at each frequency on each transmitter, we can get the CDF, as shown in Fig. 33. And the mean of data in Table 19 is 32.8 dB and standard deviation is 15.3 dB.

FIGURE 33

Cumulative distribution function of median value of each Tx at each frequency



9.3.3 Measurement results and analysis of building C scenario

After processing the original test data the entry loss of building C can be obtained. The median value of the entry loss measurement above is shown in Table 22.

TABLE 22

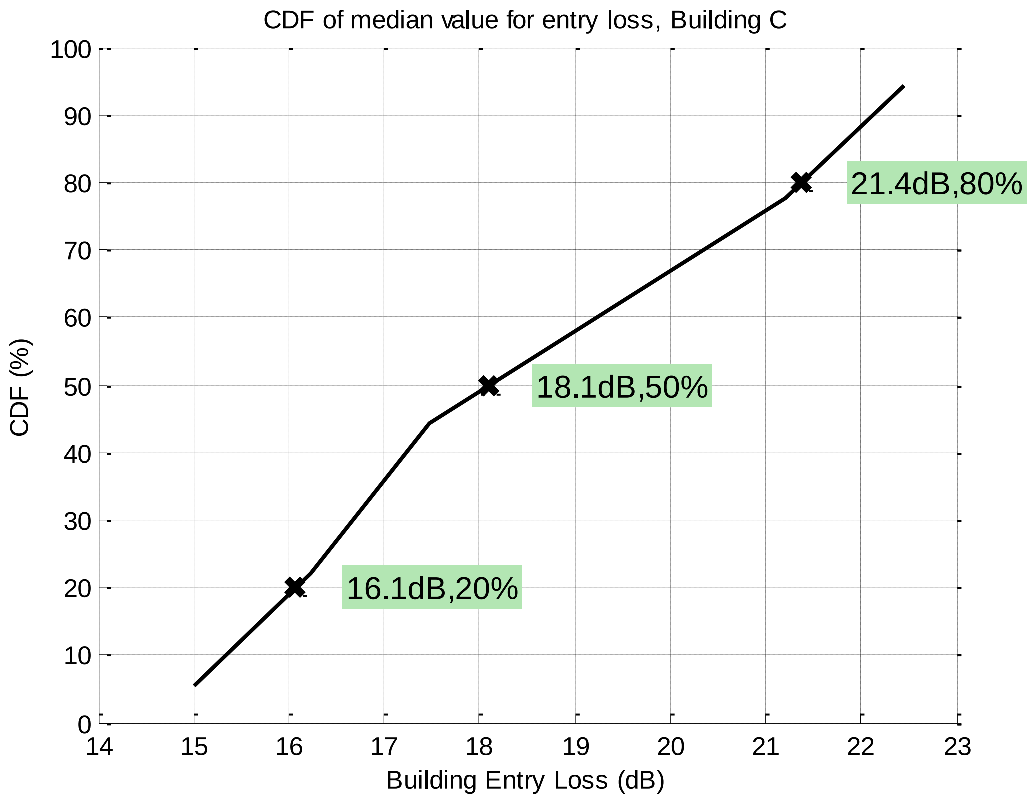
The median value of the entry loss, One Tx vs 3 Rx (Building C, unit: dB)

Frequency (MHz)	3 401	3 501	3 599	Category
Rx 4	21.5	15.0	15.7	Outer wall with glass
Rx 5	18.4	22.3	20.9	Outer wall with glass
Rx 6	18.5	19.4	22.5	Outer wall with glass

Through analysis of median values of building entry loss (data in Table 22) at each frequency on each Rx, we can get the CDF, as shown in Fig. 34. And, the mean of data in Table 20 is 19.4 dB and standard deviation is 2.7 dB.

FIGURE 34

Cumulative distribution function of median value of each Rx at each frequency



10 Building entry loss measurement at 3.5 GHz in UK

10.1 UK measurements

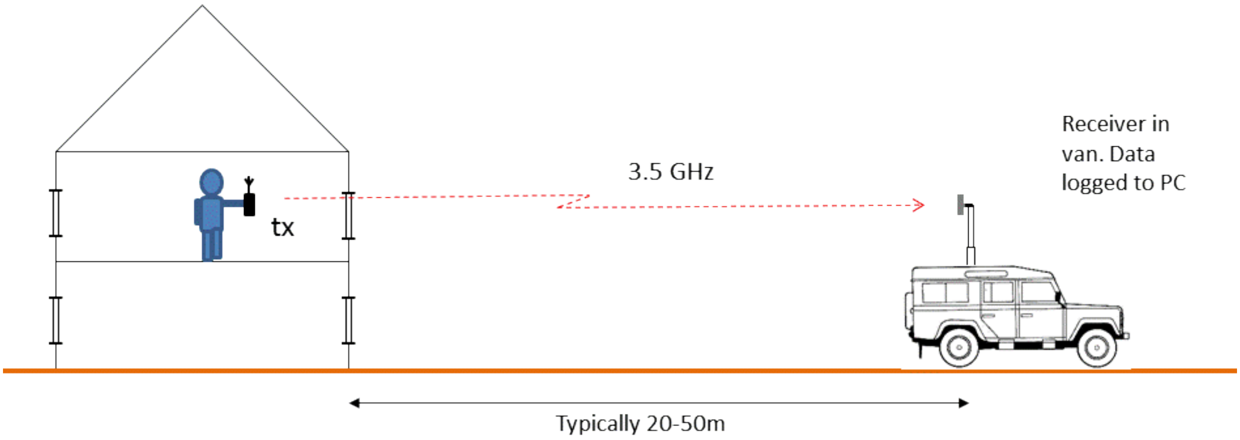
A limited campaign of measurements has been undertaken to gather 3.5 GHz entry loss data for UK buildings. The intention of this limited campaign was to inform discussions of BEL modelling within SG 3 and to develop and refine measurement methods. If the results are considered useful, it would be simple to extend the measurements, both within the UK and in other regions.

10.2 Methodology

The methodology adopted for the 3.5 GHz measurements closely follows that used in earlier UK studies (see 3J/90). A portable, handheld, transmitter is used to explore the building under test, with signals received at a transportable (vehicle-based) terminal located some tens of metres from the building (but in LoS). Figure 35 shows the arrangement.

FIGURE 35

Experimental arrangement



The pathloss measured from within the building is compared with that measured from outside the building, close to the wall facing the receiver. The 'Building Entry Loss' is then defined as the difference between the median values of the two distributions.

Given the enormous variation in entry loss seen at different points throughout a typical building (often around 30 dB), the measurements are broken down on a room-by-room basis. This seems to be the smallest degree of discretisation that is useful in practice; rooms may be characterised as, e.g. 'first-floor, away from receiver' or 'ground-floor, facing receiver'. To attempt to define positions within rooms would rapidly become very complicated and building-specific and would be unlikely to aid statistical analysis.

A separate results file is recorded for each room in the building; within each room, the engineer will walk slowly around a semi-random route that explores the entire floor-area. It has been found that this method gives results repeatable to within about 1 dB.

An important point is that the intention is that the 'outdoor reference' measurements are made at the same height as the indoor measurements. This allows the modelling of building entry loss to be decoupled from the modelling of other local environmental effects, such as clutter loss due to surrounding buildings. It should be noted that this approach is not always followed in some of the studies reported in the literature.

In the ideal case, the receiver would be located sufficiently far from the building to ensure both a plane wavefront at the exterior wall and that the difference in free-space pathloss throughout the building is negligible. In practice, the latter may be up to 6 dB and needs to be corrected for in post-processing.

10.2.1 Hardware

The test source for the measurements is a small 2W transmitter operating at around 3.5 GHz. The transmitter feeds a handheld co-linear (omnidirectional) antenna, radiating an unmodulated carrier.

The vehicle-mounted receive system consists of a flat-plate antenna mounted on an extensible mast, feeding a Rohde & Schwarz FSP-13 spectrum analyser interfaced to a PC for data logging.

10.2.2 Software

The logging software recorded the received signal at a rate (1/80 ms) sufficient to capture the fast-fading (Rayleigh) statistics of the path. This fast fading is filtered from the results reported below, but could be explicitly included in the post-processing if required. Systematic analysis of this data would be difficult, however, as the speed with which the transmitter moves is not constant.

10.3 Test locations

Four test locations have been used in this brief campaign, comprising a small residential building, two large retail 'superstores' and a small office building. Measurements in a large modern office block are also planned but have not been completed at the time of writing.

In all cases, a clear LoS was available between the outdoor terminal and an exterior wall of the building under test.

10.3.1 Terraced house

This terraced family home (built in 1880) is of traditional brick construction, and has two rooms on the ground floor, three on the first floor and one attic room in the roof-space.

FIGURE 36

Terraced house

The receiver, in this instance, was not mounted in the vehicle but on a tripod in the garden behind the house, at a range of 13.5 m from the exterior wall.

10.3.2 Small office

A small office building of traditional brick constriction (built circa 1980) was measured with the receiver vehicle in two locations, to the front and rear of the building. The accommodation is on three floors.

FIGURE 37

Small office (Google Earth)

The measurements were made at ranges of 40 m (front) and 27 m (rear). The receiver locations and the building under test are shown in the plan view below.

FIGURE 38

Plan view of small office showing receiver locations (Google Earth)

10.3.3 Retail buildings

Measurements were made in two retail buildings, both of steel-frame, brick clad construction and both incorporating a large amount of metalwork in the interior fittings. The first, ‘Retail A’ was a technology store occupying an area of 40 m × 40 m, with the receiver located at 35 m distance. Measurements were made throughout the open-plan store, logged in 9 separate files representing paths in the front, middle and back of the store and the right, middle and left sides of the building (see Fig. 39, left).

The ‘Retail B’ building (a food supermarket) is significantly larger, and measurements were made in a 20 m × 40 m subset of the floor area, as shown in Fig. 39, right). Two receiver locations were used in this case, one at around 15° to the normal from the building and the other at around 40°. In both cases the range was around 90 m.

FIGURE 39

Measurement plans – ‘Retail A’ on left, ‘Retail B’ on right (Google Earth)

Figure 40 shows a view of ‘Retail B’ from the antenna[3] height at the second receiver location.

FIGURE 40

View of ‘Retail B’ building

[3] The UHF log-periodic antenna seen in the picture is not the measurement antenna.

10.4 Results

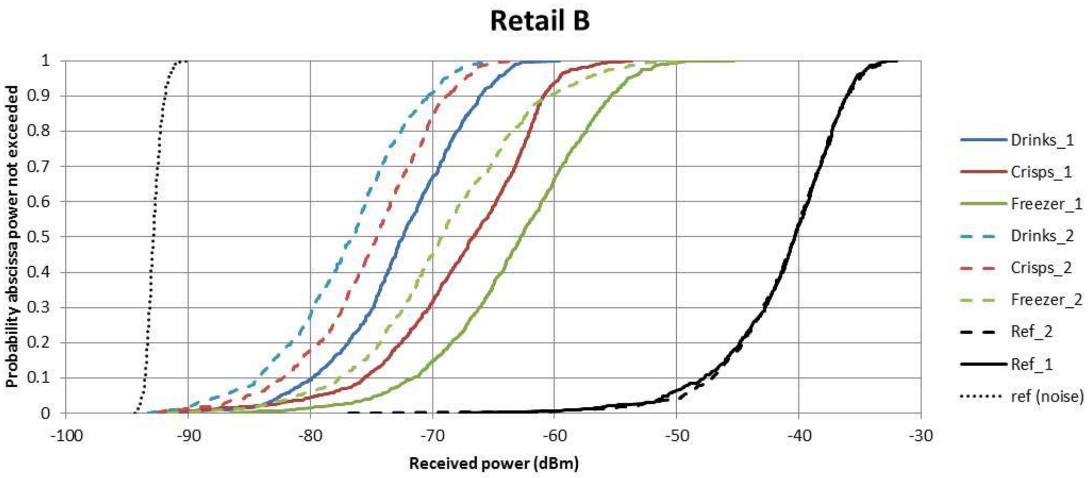
10.4.1 Building entry loss

In line with the definitions given in Recommendation ITU-R P.2040, BEL is taken to be the difference between the median field measured immediately outside the building and that measured within each room or subdivision of the building.

The BEL can be quickly estimated by inspecting the cumulative distributions of the power recorded at the outdoor receiver, as shown in Fig. 41, and comparing the indoor values with the outdoor reference at the 0.5 probability point.

FIGURE 41

Summary results for 'Retail B' measurements



This figure shows that, as might be expected, the BEL increases (by 8-10 dB) as a function of depth within the building[4,5]. The loss to the 'outdoor reference' is almost identical from the two receiver locations, but it is interesting to note that the BEL values are greater for the more oblique 'RX2' measurements. This is in line with the Fresnel expressions for transmission loss through a plane surface at different angles, though the effect is surprisingly clear and may equally be due to other effects, such as diffraction loss from clutter within the store.

The results from the 'Retail A' building (Fig. 42) are very different in character, with smaller values of loss (as might be expected for a smaller, less cluttered, store). Most interesting, however, is the fact that there is very little dependence of BEL on penetration depth – possibly due to high levels of scattered energy within the building.

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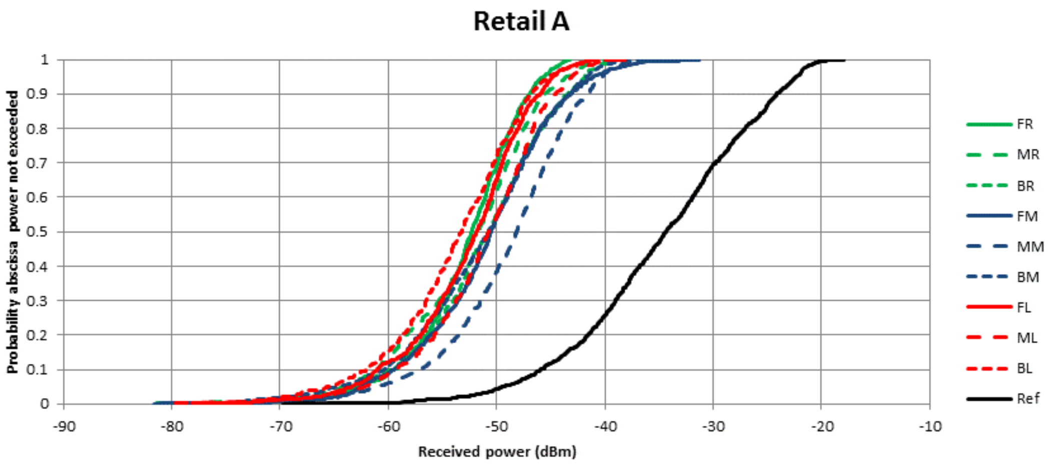
[4] The colour-coding of the traces follows that of the measurement areas in Fig. 39 (right).

[5] Note that BEL in the present definition includes both losses through the outer wall and additional losses within the building.

FIGURE 42

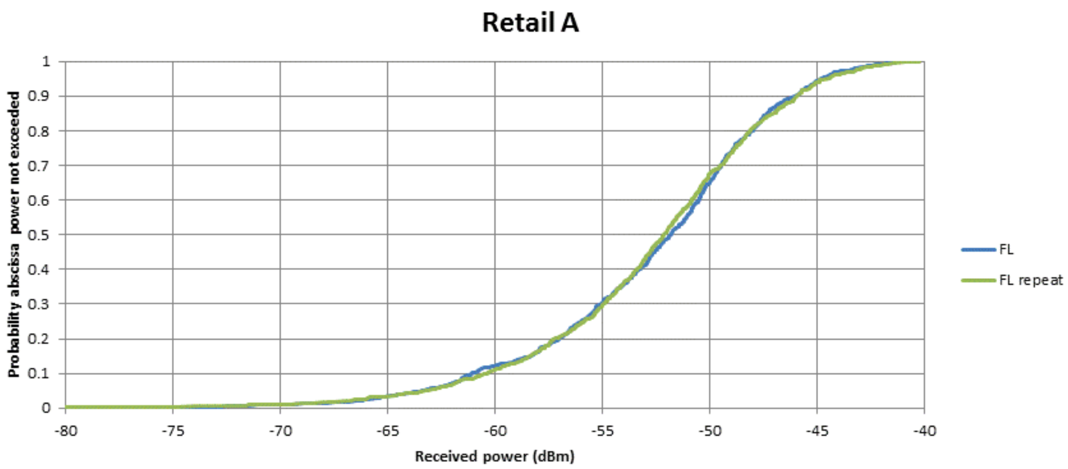
Summary results for 'Retail A' measurements



The repeatability of measurements is indicated in Fig. 43, which shows two independent sets of measurements for a single sub-section of the 'Retail A' building.

FIGURE 43

Showing repeatability of measurement



10.4.2 BEL Variability

Characterising the variability of pathloss into or out of buildings is a non-trivial problem. In the present context, we have defined variability to exclude multipath (selective fading) effects in line with the ITU-R definition of outdoor 'location variability'. This has the advantage of decoupling the statistics from consideration of radio system bandwidth, but imposes a requirement to undertake appropriate post-processing of the measured data.

As noted above, the simple nature of the present experimental arrangement[6], with data gathered at regular time intervals, but the terminal moving at arbitrary (walking) speed, precludes a very formal approach to such post-processing. For the results reported here, a 4-point moving average was

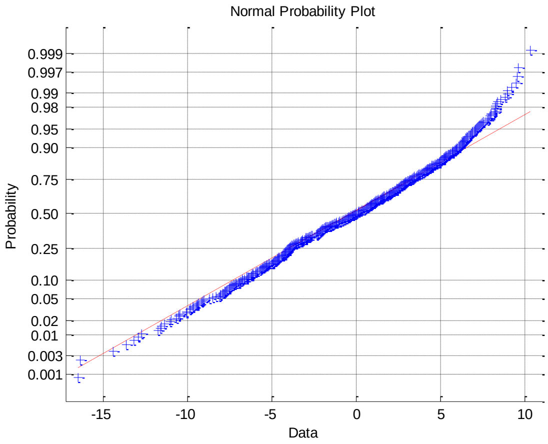
6 Such a simple approach is probably pragmatically necessary, to allow large amounts of data to be gathered rapidly.

applied to the data, which appears sufficient to remove the majority of selective fading while preserving the flat fading due to clutter and other effects.

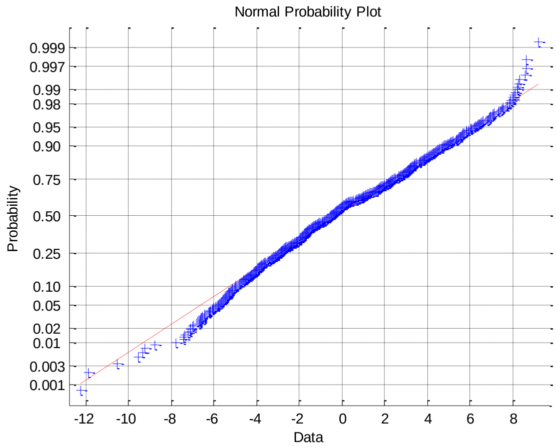
With this averaging applied, the measured data is found to be reasonably fitted[7] by a lognormal distribution, as shown in the figures below, which are normalised to the median value. Given the current paucity of data, and the occasionally poor fit to the distribution tails (such as in Fig. 44a and c), it is suggested that BEL statistics should only be modelled between decile points.

FIGURE 44

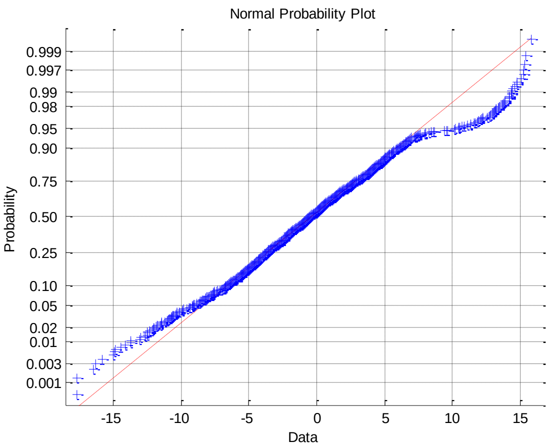
Sample loss distributions



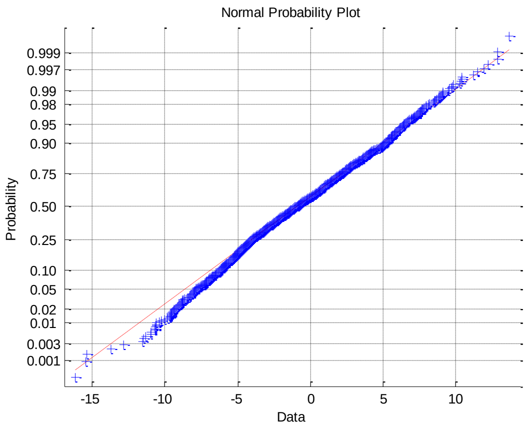
a: ‘Small office’ (Gnd floor kitchen, SD = 4.9 dB)



b: ’Retail B’ (Back), SD = 3.7 dB)



c: ‘House’ (study, SD = 5.5 dB)



d: ’Retail A’ (mid), SD = 4.4 dB)

11 Building entry loss measurements at 28 GHz

11.1 Scenario

The measurement scenario is shown in Fig. 44. The outdoor antenna was mounted on the roof of a parking garage 70 metres from the office, marked as point O in white, and the indoor antenna was mounted on a tripod on the third floor of an office building, marked yellow in Fig. 45.

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[7] Although some skewing is always evident at the low-loss tail of the distribution and occasionally at both tails.

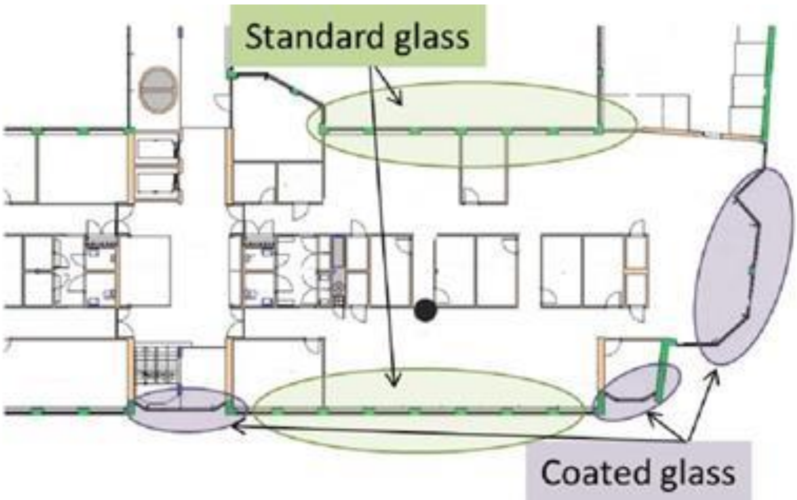
FIGURE 45

Configuration of the antennas

The office has both standard and coated window glass as indicated in Fig. 46. The indoor distance between the walls with standard glass windows is 17 metres. The office landscape was empty apart from interior walls indicated in Fig. 46, and no people were accessing the area during the measurements. The weather-controlled textile outdoor blinds were not down during the first two measurements, but they were down occasionally during the long term measurement.

FIGURE 46

Drawing of the office landscape with type of glass marked, the black dot marks the spot for the long-term measurement. The distance between the walls with standard glass windows is 17 metres



11.2 Experimental Set-up

The radio units used as transmitters and receivers in the measurements are commercially-available, all-outdoor single-carrier frequency division duplex (FDD) radio link units, operating in the 28 GHz band. They have a channel bandwidth of up to 50 MHz (56 MHz channel spacing) and modulation formats between 4 and 512 QAM, giving throughput between 94 and 406 Mbit/s at 50 MHz bandwidth. Adaptive modulation mode was enabled on the radios, which means that the modulation format depends on the mean square error detected by the radio, which in absence of additional interference can be referred to a threshold in received power.

At the indoor unit, a highly directive integrated antenna was used for all measurements. This antenna is a parabolic dish with diameter 0.24 m, 34 dBi gain, half-power beamwidth (HPBW) of 3.3 degrees, side-lobe level (SLL) below –20 dB and –30 dB at about 5 and 20 degrees, respectively. The polarization of the antennas can be set to vertical or horizontal, and the cross-polarization discrimination (XPD) is better than 30 dB within two times the HPBW. The antenna was mounted 2 metres above floor level. At the outdoor unit, both the integrated 0.24 m antenna and a vertically-polarized wide-beam slot array antenna were used in two separate measurement setups. The wide-beam antenna has a gain of 22 dBi, a HPBW of 4.3 degrees in elevation, and about 60 degrees in azimuth. The XPD is better than 25 dB within the main beam.

The angular distributions at the indoor locations were determined by rotating the indoor antenna in the azimuth domain while continuously measuring the received power. This was done initially "by hand," but in a second campaign by using a motorized rotator to find the direction-of-arrival (DOA) to the strongest multipath components (MPCs). The set-up used for the second measurement campaign with the wide-beam outdoor antenna was also used for the long-term measurements. For the long-term measurements the indoor antenna was aligned for maximum received power.

The output power was always set to have an operating microwave link connection between the radios, though the transmitted power never exceeded +18 dBm. For the long-term measurements, an attempt was made to keep the power levels as realistic as possible, lowering the transmitted power of the indoor unit to minimize the regulated safety zone around the antenna. The transmitted power from the outdoor radio was +18 dBm on the roof and the indoor unit transmitted at –10 dBm.

11.3 Data collection/analysis

The transmitted and received powers of both radios, together with the capacity of the link in both directions, were collected during all measurements. The DOA angle of the maximum received power was also noted. To study the long-term stability of a potential radio link setup, a four-day measurement was conducted, with data collection every 30 seconds.

The excess loss in this paper is defined as the increase in loss relative to a measured reference LoS level at the indoor window location A, at 70 m LoS distance (see Fig. 47), with the window open.

FIGURE 47

Attenuation for the first scenario with narrow-beam antenna on both sides, with vertical polarization (left) and horizontal polarization (right). See Table 23 for the colour legend

TABLE 23

Colour legend used in Figs 47 and 48

Colour	Excess loss
	3-10 dB
	11-20 dB
	21-30 dB
	31-40 dB
	41-50 dB
	51-60 dB

11.4 Results

The measurement results are presented in Figs 47-49. At every measured point, an operating microwave link connection was established with a modulation format between 4 and 512 QAM. The capacity of the microwave link was in agreement with the predicted capacity for the actually received power and thus the link was usually not degraded due to multipath. At a couple of points there was evidence of frequency-selective fading, as the received powers differed between the up- and down-link directions. This was due to the separation of frequency in the FDD channel (1 008 MHz separation at 28 GHz). The indoor radio was in that case moved so that the received power in both directions became equal; the movement was less than 10 cm. Minor frequency-selective fading was expected, as the path differences for possible multipaths were small.

Figure 47 visualizes the excess loss for horizontal and vertical polarization when using a narrow antenna beam also at the outdoor unit. The reason for the steep increase in excess loss when moving backwards into the office, point A to C, is because the actual LoS path becomes partially blocked by the concrete pillars between the windows. From the measurement points further into the building, point D to F, the waves can either propagate through the interior wall or diffract/reflect around the interior cubical. Multiple MPCs with similar strengths were present.

Figure 48 shows the excess loss for vertical polarization with a sector antenna at the outdoor unit. The reason for the variation in excess loss along the corridor is due to the concrete pillars, as mentioned earlier, blocking the LoS path.

FIGURE 48

Attenuation in scenario two, with wide-beam antenna at the outdoor site. See Table 23 for colour legend

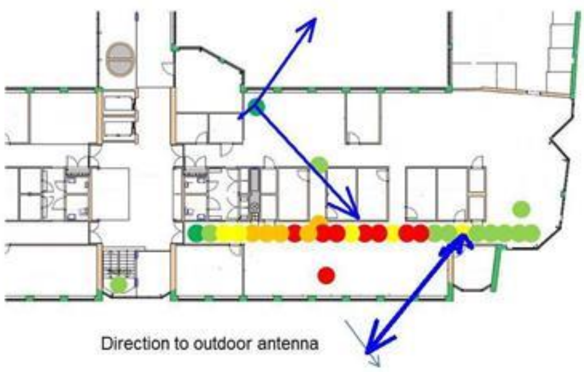
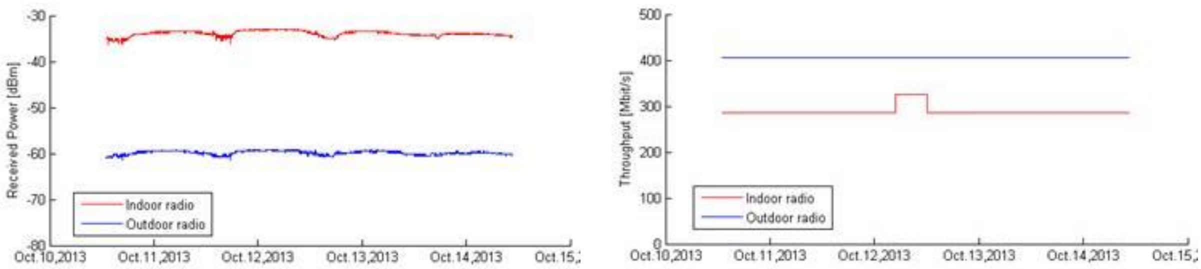


Figure 49 shows the received power and capacity from a long-term measurement during four days. The long-term measurement showed stable throughput and received power levels. The decrease in received power, occurring every afternoon, was due to outdoor sun blinds going down automatically to cover the windows. In this scenario, any major time-dependent changes of the channel were not expected, as no person had access to the office landscape during the measurements and the outdoor weather during this period was without any precipitation. The difference in received power between the outdoor and indoor radio is due to the 28 dB difference in transmitted power mentioned earlier. The capacity of the links was 406/285 Mbit/s in down-/up-link, which correlates to a modulation format of 512/64 QAM. The up- and down-link radios are independent and can send data in different modulation formats. The modulation formats, as mentioned earlier, depend on the mean square error which, if no interference is present, is directly dependent on the received power. The capacities measured are in good agreement with the modulation format expected for the measured received power, indicating no degradation due to interference/multipath.

FIGURE 49

Received power and throughput over 4 days; the difference in received power is due to difference in transmitted power; the indoor unit transmitted 28 dB lower power



A loss of about 3-5 dB was measured in the standard glass window and about 30 dB in the coated window, which is in good agreement with other[8] observations.

At the indoor unit there was usually more than one incoming direction of waves. The attenuation in Figs 47 and 48 refers to the strongest path. If a LoS path was available, this was always the clearly dominating path, but in most other cases power was received from more than one incoming direction. Two examples of this are shown in Fig. 48. The lengths of the arrows indicate the linear relation between the received power in different DOA directions (a doubly-long arrow corresponds to 3 dB higher received power). The length of the arrows is normalized to the highest received power at that measured point and is not related to the length of the arrows at the other location. As can be seen at the top left point there is almost equal power from two directions. All waves seem to reach the point after passing through the narrow passage between the indoor cubicles, either through multiple reflection or diffraction. One path obviously also includes a reflection from the windows behind the measurement point. For the lower right measurement point, the paths are somewhat more difficult to explain. This case involves a concrete wall and an evacuation staircase with coated glass, blocking the LoS, which the signal is not penetrating so easily. As can be seen, the strongest path is propagating via a final diffraction on the edge of the blocking concrete wall in the proximity of the antenna. Regarding its path before the diffraction, it is not clear if it is reflection/diffraction on the concrete pillars between the windows or multiple reflections within the office space. Beyond this strongest path, 6 paths reaching the measurement point by reflection were also measured. Since these are about 10 dB below the strongest one, they are difficult to see in the picture.

8 Zhao, H., *et al.*, "28 GHz Millimetre Wave Cellular Communication Measurements for Reflection and Penetration Loss in and around Buildings in New York City", Proc. IEEE International Conference on Communications (ICC 2013), June 2013.

11.5 Conclusion

The results show that attenuation/excess loss limits the coverage, rather than multipath interference. In the scenario studied, coverage was obtained at all measured locations with a loss between 3 and 60 dB above the reference level at 70 m LoS distance. If all windows in the office had been of the coated glass kind, then at least 20 dB higher excess loss would be expected and the coverage would be significantly more limited. Thus, the deployment opportunities strongly depend on the specific location and the kind of windows that are present.

It is concluded that the indoor environment at this location is not isolated from the outdoor cell. Thus, at many locations it will be possible to provide, for example, a backhaul link between an indoor wall-mounted high gain antenna and a similar outdoor antenna, even when the indoor excess loss is extensive.

12 Measurements at 5.2 GHz

The experimental results shown in Table 24 were obtained at 5.2 GHz through an external building wall made of brick and concrete with glass windows. The wall thickness was 60 cm and the window-to-wall ratio was about 2:1.

TABLE 24

Example of building entry loss

Frequency	**Office**	
	Mean	Standard deviation
5.2 GHz	12 dB	5 dB

Table 25 shows the results of measurements at 5.2 GHz through an external wall made of stone blocks, at incident angles from 0° to 75°. The wall was 400 mm thick, with two layers of 100 mm thick blocks and loose fill between. Particularly at larger incident angles, the loss due to the wall was extremely sensitive to the position of the receiver, as evidenced by the large standard deviation.

TABLE 25

Loss due to stone block wall at various incident angles

Incident angle (degrees)	0	15	30	45	60	75
Loss due to wall (dB)	28	32	32	38	45	50
Standard deviation (dB)	4	3	3	5	6	5

Annex 1

Building entry loss in point-to-area applications below 3 GHz

The following information has been found helpful in planning broadcast and other point-to-area radio services.

For *indoor reception* two important parameters must also be taken into account. The first is the BEL and the second is the variation of the BEL due to different building materials. The standard deviations, given below, take into account the large spread of BEL but do not include the location variability within different buildings. It should be noted that there is limited reliable information and measurement results about BEL. Provisionally, BEL values that may be used are given in Table 26.

TABLE 26

Building entry loss[(1)], L_{be}, σ_{be}

F	Median value, L_{be} (dB)	Standard deviation, σ_{be} (dB)
0.2 GHz	9	3
0.6 GHz	11	6
1.5 GHz	11	6

(1) These values may have to be updated when more experimental data become available.

For frequencies below 0.2 GHz, L_{be} = 9 dB, σ_{be} = 3 dB; for frequencies above 1.5 GHz, L_{be} = 11 dB, σ_{be} = 6 dB. Between 0.2 GHz and 0.6 GHz (and between 0.6 GHz and 1.5 GHz), appropriate values for L_{be} and σ_{be} can be obtained by linear interpolation between the values for L_{be} and σ_{be} given in Table 7 for 0.2 GHz and 0.6 GHz (0.6 GHz and 1.5 GHz).

The field-strength variation for indoor reception is the combined result of the outdoor variation, σ_L, and the variation due to building attenuation, σ_{be}. These variations are likely to be uncorrelated. The standard deviation for indoor reception, σ_i can therefore be calculated by taking the square root of the sum of the squares of the individual standard deviations.

$$\sigma_i = \sqrt{\sigma_L^2 + \sigma_{be}^2} \qquad \text{dB} \tag{8}$$

where σ_L is the standard deviation of location variability.

For example, for digital emissions with bandwidth greater than 1 MHz, at VHF, where the signal standard deviations are 5.5 dB and 3 dB respectively, the combined value is 6.3 dB. In Band IV/V, where the signal standard deviations are 5.5 dB and 6 dB, the combined value is 8.1 dB.