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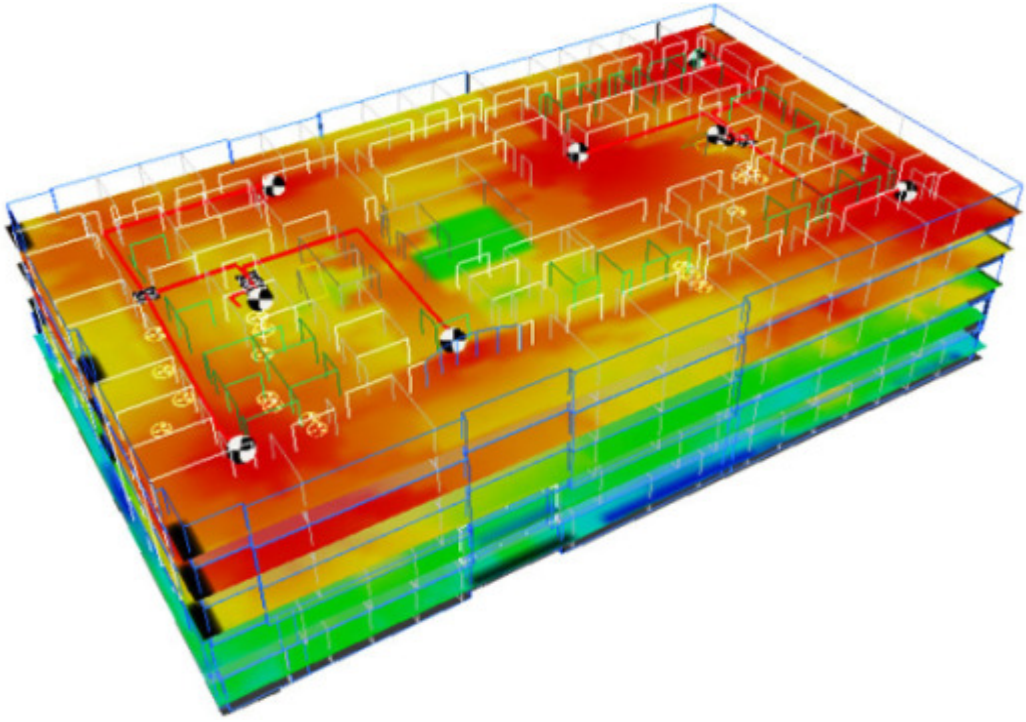
Propagation losses into and within buildings in the 800, 900, 1800, 2100 and 2600 MHz bands

Survey for Ofcom



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1. Scope

This report details work undertaken by Real Wireless for Ofcom to investigate propagation losses into and within buildings in the 800, 900, 1800, 2100 and 2600MHz bands. The aim of this work has been to gather, review and analyse evidence on the dependence of building propagation losses within buildings as a function of the following key variables:

- Depth
- Frequency
- Building type and geometry

The steps followed within this study were as follows:

1. Gather existing and newly-identified literature relating to this issue, including but not limited to:
    - Journal papers, books, conference proceedings and research reports on building propagation, including both modelling studies and measurements (including both isolated material sample measurements and in-situ building measurement campaigns)
    - Ofcom publications, including the mobile liberalisation consultation documents and Spectrum Efficiency Scheme reports
    - COST and ITU reports and recommendations
    - Operator (and other stakeholder) responses to information requests and previous consultations. [1]
2. List relevant literature, summarise and collate the findings in a coherent and clearly-presented fashion, considering both mean losses and the standard deviation (and probability distribution where available). Tabulate and graph results according to the key variables and where feasible conduct regression analysis to determine the dependence of loss according to the key variables with different weightings amongst the reference sources.
3. Prepare a report to capture results and present findings to Ofcom.

[1] Note that this confidential section on stakeholder responses is not included in the public version of this report

2. Background

The February 2009 mobile liberalisation consultation [1] defined building penetration loss as:

"The difference (in decibels) between the median of the location variability of the signal level at the building location, as predicted by the outdoor propagation model, and the signal level inside the building at the same height above ground, with multi-path fading spatially averaged for both signals"

This same definition has (implicitly) been used in all of the subsequent work by Ofcom and will be adopted here.

The building penetration loss is only one component of the overall propagation loss between a base station and an (indoor) mobile device, and all need to be considered to determine the overall impact on network performance. The same consultation also set out the framework illustrated in Figure 2-1 for considering these losses. Although later work – notably the January 2012 consultation [2] – does not explicitly calculate a fade margin the same general formulation for the total loss is applied.

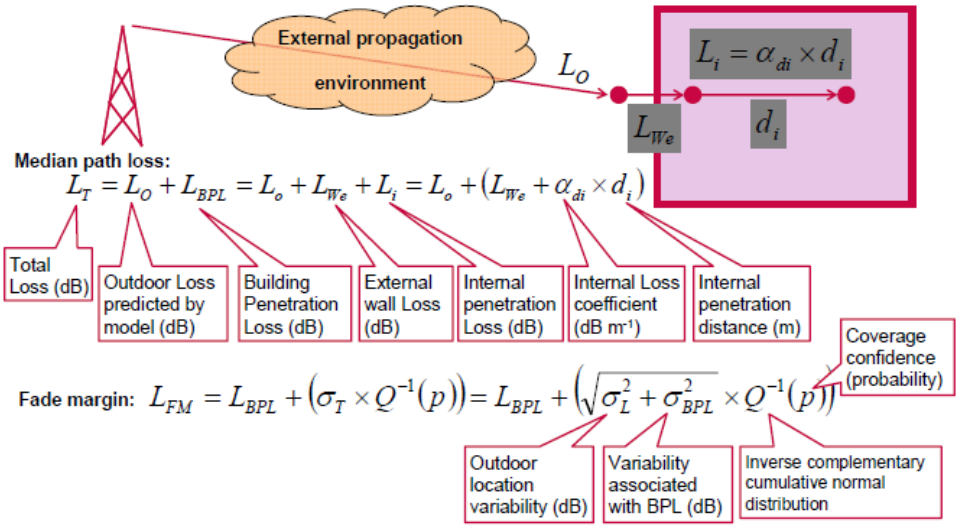


Figure 2-1: Formulation of total propagation loss from February 2009 consultation [1]

In the main, responses to this framework have focused on the building penetration losses rather than the outdoor losses. In this report we gather and summarise available evidence for these losses, especially in respect of three key variables:

- Frequency band
- Depth (or consistency) of penetration
- Building type (or clutter type)

Evidence gathered includes:

- Published material in the open literature, prioritising measurements over models and in-situ measurements over laboratory measurements

- Confidential (and public) information provided by mobile operators in response to previous consultations and information requests [2]

[2] Note that this confidential section on stakeholder responses is not included in the public version of this report

3. The physics of radio wave propagation into buildings

It is out of scope of this report to investigate the physics of in-building propagation in any greater detail than previous Ofcom consultations have covered, but to provide context to the data presented later, we summarise here the main outcomes of the review conducted in support of the February 2009 consultation.

The main propagation mechanisms of relevance are:

- Absorption loss due to penetration through bulk materials (e.g. solid, homogeneous walls).
- Diffraction around edges (e.g. window frames, reinforcement rods etc.)
- Scattering from rough surfaces and objects small compared with a wavelength (e.g. furniture and rough walls).
- Multipath effects (e.g. from the combination of multiple reflections from internal walls).
- Waveguide effects (e.g. along long, straight corridors).

These mechanisms exhibit different frequency dependencies, which were summarised in the table reproduced in Table 3-1. The balance between the mechanisms, and hence the overall frequency dependency, will depend on the materials and geometry of the building in question as well as to a lesser extent the geometry of the surrounding buildings and the relative placement of the transmitter and receiver. Beyond this simple summary, it is important to recognise that resonance and multipath effects mean that losses over a given range can be positively or negatively dependent on frequency, even within a single mechanism.

Table 3-1: Summary table for impact of frequency on loss according to propagation mechanisms, from February 2009 consultation [1]

Effect	Impact on loss at high frequency
Loss through uniform external walls and metallised glass will increase with frequency	⇧
Loss through large apertures with minimal conductivity (plain glass windows)	=
Loss in regions dominated by diffraction and no line-of-sight	⇧
Losses through smaller windows may decrease with frequency if wavelength close to size (~25cm)	⇩
Loss at particular points in presence of strong multipath may increase or decrease with frequency over limited frequency ranges	⇳
Loss through internal walls and through floors will increase with frequency, so greater differences for greater target depths	⇧
Corridors may exhibit unusually low penetration loss	= or ⇩

One specific example in [3], based on physical modelling, illustrates the complexity of these effects. This paper models a double-glazed window unit within a brick wall with the transmitter and receiver placed either side of this wall. Realistic material parameters and dimensions were used. This paper shows that when the transmitter and receiver were aligned with the centre of the window, the loss reduced with frequency from 100 MHz to 300 MHz, although the difference between 300 MHz and 3GHz is small (with the loss at both 300MHz and 3GHz being approximately 5dB in one example given). This arises due to aperture effects: the large wavelength at the lower frequency produces aperture losses in the window, which become negligible at the higher frequencies. However, when the transmitter and receiver were moved so that the direct propagation path passed through the wall rather than the window, the loss increased substantially between 300 MHz and 3 GHz (with the loss at 300MHz being 15dB as opposed to 25dB at 3GHz in one example given). In this case the conductivity of the brick wall causes ohmic losses which increase directly with frequency. At 3 GHz a high degree of variability is evident due to multipath effects which arise within the double glazing unit and elsewhere. Finally this paper presents results which illustrate how the loss varies not only with frequency but also with angle of arrival (generally increasing for a higher angle of arrival). Comparisons of loss with frequency over a limited range can therefore produce a loss which either rises or falls, depending on the specific range examined and the path geometry.

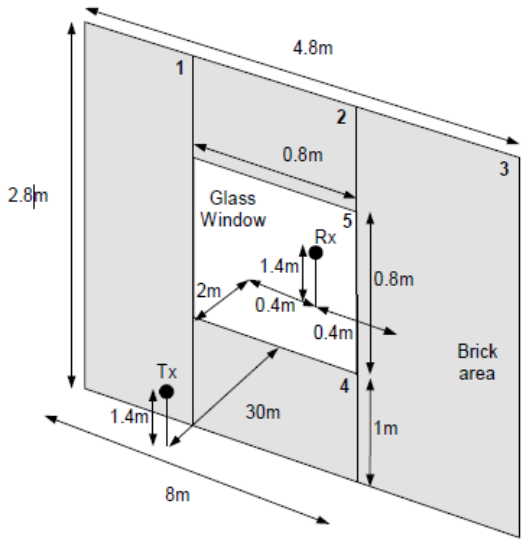


Figure 3-1: Geometry of double glazed window set into brick wall, as analysed in [3]

4. Ofcom assumptions in current and previous publications

This section sets out and compares the assumptions made by Ofcom in support of consultations and other publications up to and including the January 2012 consultation [2].

4.1 Assumptions in the September 2007 mobile spectrum liberalisation consultation

In the September 2007 consultation relating to the liberalisation of 900 MHz and 1800 MHz spectrum, [4], the assumptions made regarding building penetration losses were 10dB, 12dB and 13dB for the average losses at 900 MHz, 1800 MHz and 2100 MHz respectively. The variability was assumed to be 6dB at all frequencies. No variation with building or clutter type was included.

This consultation document noted that "The factors affecting the penetration loss involved in propagation into buildings are complex and vary from building to building. However on balance lower frequencies are generally better than higher frequencies for penetrating deep into buildings."

It also gave a brief overview (Annex 8, §A8.15) of the relevant propagation mechanisms.

A sensitivity analysis of the scale of networks required to meet given coverage and capacity targets was included at §A8.37 which included the following cases:

1. That the mean BPL at 900MHz, 1800MHz and 2100MHz does not change from its 900 MHz value
2. That the BPL at 2100 MHz is higher than the central case, at 15 dB rather than 13 dB

These assumptions are summarised below in Table 4-1.

Table 4-1: BPL cases investigated in September 2007 consultation [4]

	900 MHz	1800 MHz	2100 MHz
Mean BPL – central case	10 dB	12 dB	13 dB
Mean BPL – low case	10 dB	10 dB	10 dB
Mean BPL – high case	10 dB	12 dB	15 dB
BPL standard deviation	6 dB	6 dB	6 dB

4.2 Assumptions in the February 2009 mobile spectrum liberalisation consultation

This consultation [1] took account of responses from stakeholders to the September 2007 consultation, notably the following main points (§A13.207 *ff*):

- That the BPL values used in September 2007 were (variously) both too high and too low
- That BPL should vary with clutter type to represent the variation according to both the building under consideration and its surrounding environment
- That losses could vary both positively and negatively with frequency
- That BPL varies with the depth of penetration and both shallower and deeper penetration should be considered
- That fade margin varies with coverage confidence and that values other than the 90% assumption used would be appropriate. The consultation assumed a coverage confidence of 90%, but respondents questioned that assumption, asserting that both higher (95%) and lower (80%) values were appropriate.

The consultation provided an overview of the relevant propagation mechanisms and effects, concluding that (§A13.234):

"Any given building will be a mixture of these effects, so a large spread of values is anticipated relative to the overall trend. Nevertheless, the general trend of increasing loss with frequency arising from the skin effect and other mechanisms suggests an overall trend to increase with frequency, particularly when the penetration depth into a building is high. The frequency variation might thus take the form of Figure 4-1for any given building"

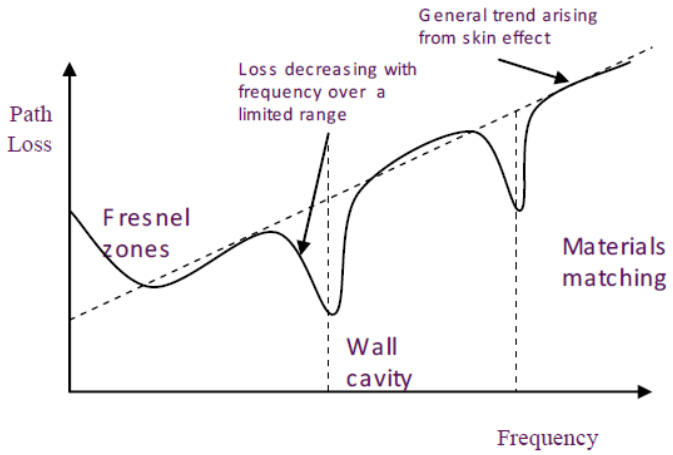


Figure 4-1: Extract from February 2009 consultation [1]

An overview of measurements was provided in this consultation also, notably a study by Qualcomm [8] and the COST 231 project [16] plus an extensive list of open literature. The overall finding from this literature survey was:

"There is a clear trend for BPL to increase [with frequency] based on this data, but the variability of data amongst buildings at a given frequency is substantially larger than the variation of the mean with frequency. Noting that some of this variation may also be due to

methodological differences amongst authors, this makes it difficult to assert a firm value for the variation in the mean."

The assumptions from September 2007 were compared with the comments from mobile operators with the following outcomes:

- Low BPL compared with all Mobile Network Operator (MNO) values for dense urban clutter.
- Lower BPL than all but one set of MNO values for urban clutter.
- Approximately in the middle of the range of BPL values for suburban clutter.
- Lower than all but one set of MNO values for rural clutter.
- Similar trend with frequency to those who asserted any variation.

As a result, a new set of assumptions was created. In contrast to the previous work, the new assumptions allowed the BPL to vary with depth (to allow examination of shallower and deeper penetration cases) and clutter type (in response to operator feedback).

Table 4-2: BPL assumptions from February 2009 consultation [1]

Depth 0	Increasing with Frequency (Rising) (Base case)		
Frequency	Dense urban	Urban	Suburban
900 MHz	7.0	5.0	3.0
1800 MHz	7.9	5.9	3.9
2.1 GHz	8.6	6.6	4.6

Depth 1	No Variation with Frequency (Constant)			Increasing with Frequency (Rising) (Base case)			Increasing with Frequency (Rising at higher rate)		
Frequency	Dense urban	Urban	Suburban	Dense urban	Urban	Suburban	Dense urban	Urban	Suburban
900 MHz	11.5	9.5	7.5	11.5	9.5	7.5	11.5	9.5	7.5
1800 MHz	11.5	9.5	7.5	13.1	11.1	9.1	19.5	17.5	15.5
2.1 GHz	11.5	9.5	7.5	14.0	12.0	10.0	21.5	19.5	17.5

Depth 2	No Variation with Frequency (Constant)			Increasing with Frequency (Rising) (Base case)			Increasing with Frequency (Rising at higher rate)		
Frequency	Dense Urban	Urban	Subur -ban	Dense Urban	Urban	Subur -ban	Dense Urban	Urban	Subur -ban
900 MHz	14	12	10	14	12	10	14	12	10
1800 MHz	14	12	10	16	14	12	22	20	18
2.1 GHz	14	12	10	17	15	13	24	22	20

The depth 2 base case is identical to the September 2007 assumptions in suburban areas.

The depth 0 and depth 1 cases were derived from the depth 2 case using a model of the form:

$$L_B = L_{W_e} + \alpha_{di} d_i$$

where the following values from Table 4-3 were assumed, referencing COST231 and a previous Ofcom research project [18]. Note that the L_{W_e} values are at the lower end of the range suggested by COST231 at 2100 MHz.

Table 4-3: Parameters for deriving BPL values in the February 2009 consultation [1]

	900 MHz	1800 MHz	2100 MHz
L_{W_e} (dB)	2.5	3.3	4.0
α_{di} (dB/m)	0.5	0.58	0.6

It was noted that the specific depth corresponding to the depth 2 case was uncertain given the wide range in losses associated with particular buildings. Although they would correspond to 15m in the case of the parameters used, the main justification for these values was that they "are in a reasonable and realistic range for good in-building coverage given the comparison with MNO evidence cited".

The standard deviation of BPL was not altered from previously, i.e. 6 dB across all cases.

4.3 Assumption in advice to government regarding mobile liberalisation, October 2010

This advice to government [5] further refined the analysis of the previous mobile liberalisation consultations and focused on the Depth 2 case introduced in the February 2009 consultation with a range spanning the "most plausible values" consisting of a "Depth 2 – base case" and a "Depth 2 – rising faster" case. It stated that:

"We believe the true answer, in terms of average effect, most likely lies somewhere within this range, but we do not have a view as to exactly where."

The outcome of the analysis indicated some technical advantages to holders of 900 MHz spectrum, but caveated these advantages as follows:

"However, the importance of this advantage depends strongly on the construction of the buildings, with relatively little or no advantage experienced for buildings of relatively light attenuation or where users are not particularly deep within the building (e.g. they may be close to windows). Under such circumstances the throughput performance at both frequencies is relatively similar and little advantage may be experienced for users on the 900 MHz network."

Some sensitivity results for depth 0 and depth 1 were also shown.

The assumptions for mean BPL are shown in Table 4-4. These align closely with the assumptions from February 2009, but add a rural category and slightly increase the 2.1 GHz losses in the depth 0 case.

Table 4-4: Mean BPL assumptions from October 2010 advice to government [5][3]

Building penetration depth scenario	Depth 0							
	Mean increasing with frequency – **Base Case**				Mean **rising faster** with frequency			
Clutter*	DU	U	S	R	DU	U	S	R
900 MHz	7.0	5.0	3.0	3.0	7.0	5.0	3.0	3.0
2100 MHz	9.0	7.0	5.0	5.0	16.0	14.0	12.0	12.0
Building penetration depth scenario	Depth 1							
	Mean increasing with frequency – **Base Case**				Mean increasing with frequency – **Base Case**			
Clutter*	DU	U	S	R	DU	U	S	R
900 MHz	11.5	9.5	7.5	7.5	11.5	9.5	7.5	7.5
2100 MHz	14.0	12.0	10.0	10.0	21.5	19.5	17.5	17.5
Building penetration depth scenario	Depth 2							
	Mean increasing with frequency – **Base Case**				Mean **rising faster** with frequency			
Clutter*	DU	U	S	R	DU	U	S	R
900 MHz	14.0	12.0	10.0	10.0	14.0	12.0	10.0	10.0
2100 MHz	17.0	15.0	13.0	13.0	24.0	22.0	20.0	20.0

The advisory document also introduced a set of assumptions where the standard deviation varies with frequency and depth, and another case where it is independent of depth but does rise with frequency, as shown in Table 4-5.

[3] Note on this table at Depth 1 the right hand column should have been labelled Mean rising faster with frequency as for the other two depths but there was a misprint in the original table.

Table 4-5: BPL standard deviation values from October 2010 consultation [5]

Building penetration depth scenario	Depth 0	
	Mean increasing with frequency – **Base Case**	Mean **rising faster** with frequency
900 MHz	3.0	4.0
2100 MHz	3.0	6.0
Building penetration depth scenario	**Depth 1**	
	Mean increasing with frequency – **Base Case**	Mean **rising faster** with frequency
900 MHz	4.5	6.0
2100 MHz	4.5	9.0
Building penetration depth scenario	**Depth 2**	
	Mean increasing with frequency – **Base Case**	Mean **rising faster** with frequency
900 MHz	6.0	8.0
2100 MHz	6.0	12.0

Building penetration depth scenario	**All depths (0, 1 and 2)**	
	Mean increasing with frequency – **Base Case**	Mean **rising faster** with frequency
900 MHz	6.0	8.0
2100 MHz	6.0	12.0

4.4 Assumptions in the March 2011 consultation

The March 2011 consultation [6] introduced the use of a 'Depth 2+' assumption, created to represent a penetration depth midway between the "depth 2: base case" and "depth 2: rising faster with frequency". The values used are also interpolated/ extrapolated for the different carrier frequencies of interest in this consultation. The values shown in Table 4-6 are used for the mean and standard deviation of BPL.

Table 4-6: BPL mean and standard deviation assumptions from March 2011 consultation [6]

Building penetration depth scenario	Depth 1				Depth 2+			
Clutter*	DU	U	S	R	DU	U	S	R
800 MHz	-11.2	-9.2	-7.2	-7.2	-13.6	-11.6	-9.6	-9.6
1800 MHz	-13.3	-11.3	-9.3	-9.3	-18.8	-16.8	-14.8	-14.8
2600 MHz	-15.0	-13.0	-11.0	-11.0	-23.1	-21.1	-19.1	-19.1

Building penetration depth scenario	Depth 1	Depth 2+
800 MHz	6.0	7.0
1800 MHz	6.0	9.0
2600 MHz	6.0	9.0

4.5 Assumptions in cost of 800 MHz coverage obligation study

It is also worth noting that a study undertaken by Real Wireless on the cost of extending the 800 MHz coverage obligation [7] used the depth 2+ assumptions for suburban and rural clutter types consistent with the March 2011 consultation, i.e.:

- Mean BPL @ 800 MHz = 9.6 dB
- BPL standard deviation @ 800 MHz = 7 dB

4.6 Assumptions in the January 2012 consultation

The January consultation [2] extends the previous analysis by explicitly varying the depth for different users across a wide range (five different depths drawn from a uniform distribution) in the same simulation. It noted that 'depth' was intended to represent a distribution of easier and harder to reach locations rather than absolute depths.

The depth 0, 1 and 2 cases were found to notionally represent depths of 1, 10 and 15m. A model of the form $L_B = L_{W_e} + \alpha_{di} d_i$ was again used, with the parameters shown in Table 4-7.

Table 4-7: Depth modelling parameters from January 2012 consultation [2]

	800 MHz	900 MHz	1800 MHz	2100 MHz	2600 MHz
	All clutter environments				
α_{di} – Lower bound	0.32	0.32	0.32	0.32	0.32
α_{di} – Upper bound	0.65	0.72	1.14	1.23	1.36
	Suburban/Rural				
L_{We} – Lower bound	1.53	1.53	1.53	1.53	1.53
L_{We} – Upper bound	3.06	3.27	4.49	4.77	5.14
	Urban				
L_{We} – Lower bound	2.87	2.87	2.87	2.87	2.87
L_{We} – Upper bound	5.72	5.93	7.15	7.43	7.81
	Dense urban				
L_{We} – Lower bound	4.20	4.20	4.20	4.20	4.20
L_{We} – Upper bound	8.39	8.60	9.82	10.10	10.47

Note that the corresponding February 2009 parameters lie between the upper and lower bounds of this range. Applying these parameters for the relevant depths results in the following median values for the suburban case as shown in Table 4-8 (the other clutter types are also presented).

Table 4-8: Median BPL values for suburban clutter from January 2012 consultation [2]

Table 4: Median BPL values – Suburban/Rural – Lower bound

Depth (metres)	800 MHz (dB)	900 MHz (dB)	1800 MHz (dB)	2100 MHz (dB)	2600 MHz (dB)
1	1.85	1.85	1.85	1.85	1.85
5	3.15	3.15	3.15	3.15	3.15
10	4.77	4.77	4.77	4.77	4.77
15	6.39	6.39	6.39	6.39	6.39

Table 5: Median BPL values – Suburban/Rural – Upper bound

Depth (metres)	800 MHz (dB)	900 MHz (dB)	1800 MHz (dB)	2100 MHz (dB)	2600 MHz (dB)
1	3.71	3.99	5.63	6.00	6.50
5	6.29	6.86	10.17	10.90	11.92
10	9.55	10.46	15.86	17.06	18.72
15	12.79	14.06	21.54	23.20	25.50

Note that the 15m upper bound assumptions yield higher values of loss than the corresponding assumptions in any previous consultation.

The standard deviation was also varied as shown in Table 4-9 (where 'min var' is used along with the lower bound mean values and 'max var' with the upper bound).

Table 4-9: BPL standard deviation values from January 2012 consultation [2]

Frequency (MHz)	BPL standard deviation (dB)	
	Min var	Max var
800	4.0	8.0
1800	5.4	10.8
2600	6.0	12.0

The median BPL values in tables 4 to 9 of the January 2012 consultation are graphed in Figure 4-2 to Figure 4-4:

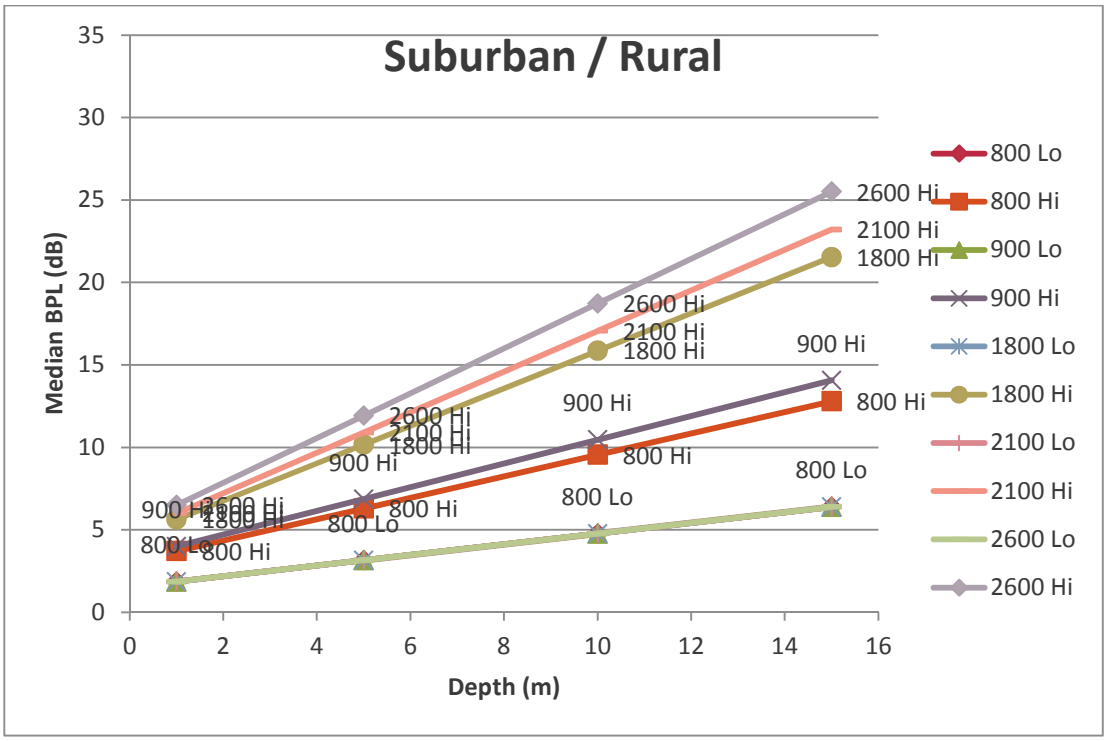


Figure 4-2: Graph of median BPL versus depth for suburban and rural areas from January 2012 consultation [2]

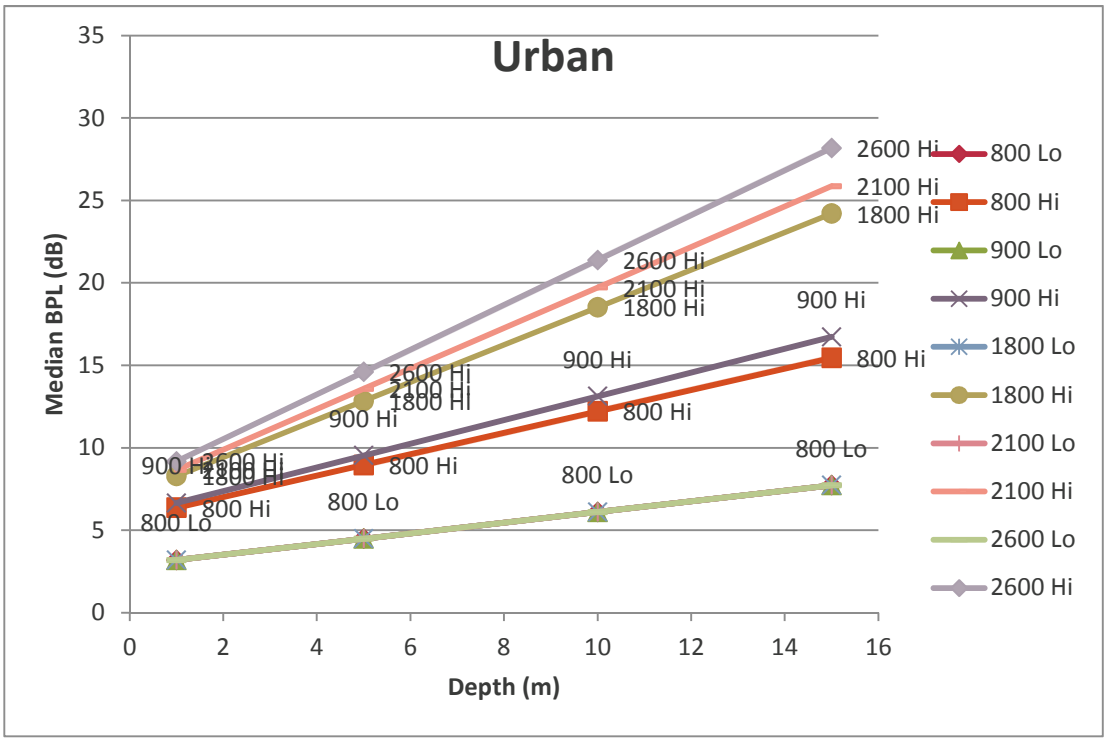
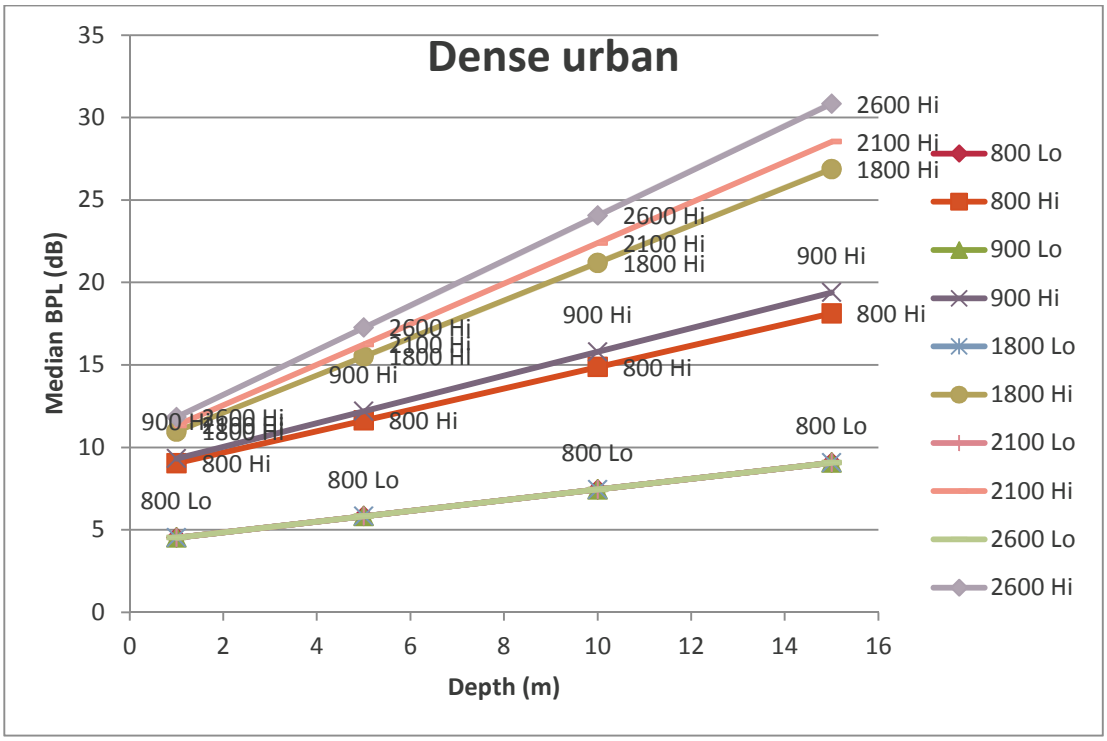


Figure 4-3: Graph of median BPL versus depth for urban areas from January 2012 consultation [2]


Dense urban
Median BPL (dB)
Depth (m)
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
2600 Hi
2100 Hi
1800 Hi
900 Hi
800 Hi
800 Lo
800 Lo
900 Hi
800 Hi
800 Lo
800 Lo
800 Lo
900 Hi
800 Hi
800 Lo
800 Lo
900 Hi
800 Hi
800 Lo

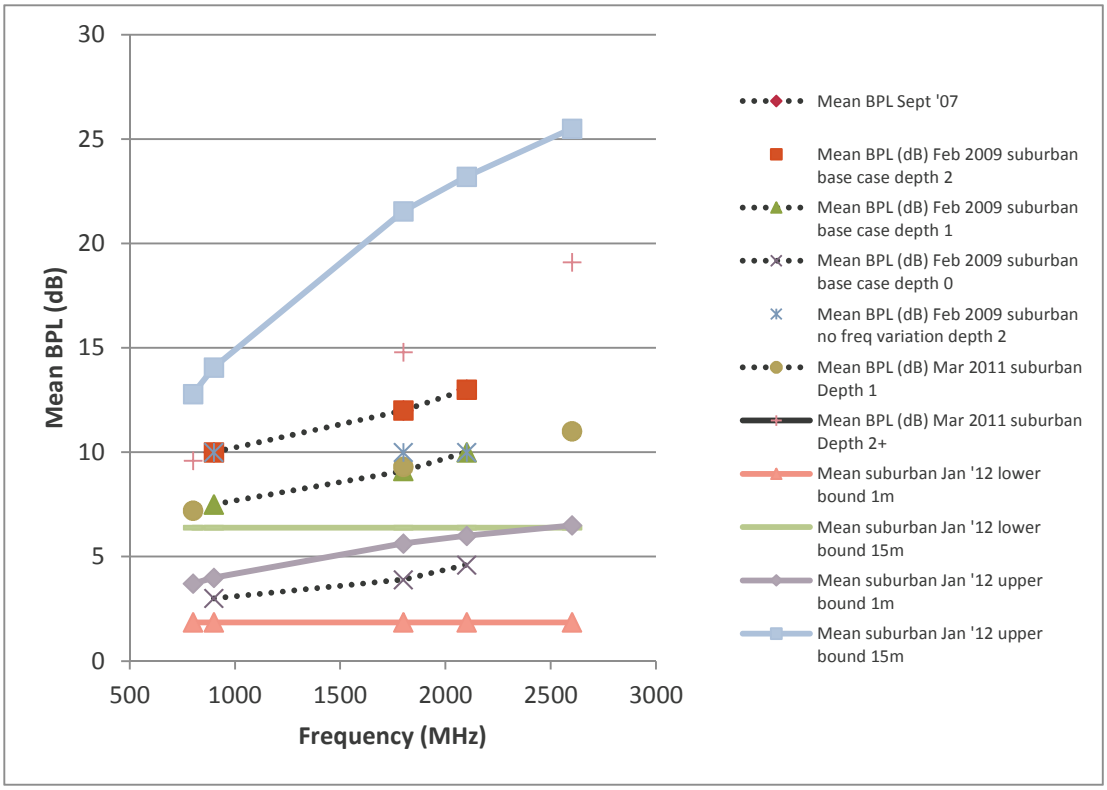


Figure 4-5: Comparison of mean BPL assumptions used by Ofcom

A summary of the key cases from each publication is captured in Table 4-10.

Table 4-10: Summary of key BPL-related assumptions in Ofcom publications

		Frequency (MHz)					
		800	**900**	**1800**	**2100**	**2600**	**Frequency exponent (dB/decade)**
Sept '07	Mean BPL (dB) Sept 07		10	12	13		8.2
	Sept 07 Standard deviation		6	6	6		
Feb '09	Mean BPL (dB) Feb 2009 suburban base case depth 2		10	12	13		8.2
	Mean BPL (dB) Feb 2009 suburban base case depth 1		7.5	9.1	10		6.8
	Mean BPL (dB) Feb 2009 suburban base case depth 0		3	3.9	4.6		4.3
	Mean BPL (dB) Feb 2009 suburban no freq variation depth 2		10	10	10		0.0
Mar '11	Mean BPL (dB) Mar 2011 suburban Depth 1	7.2		9.3		11	7.4
	Mar 11 depth 1 standard deviation	6		6		6	
	Mean BPL (dB) Mar 2011 suburban Depth 2+	9.6		14.8		19.1	18.6
	Mar 11 depth 2+ standard deviation	7		9		9	
Jan '12	Mean suburban Jan '12 lower bound 1m	1.85	1.85	1.85	1.85	1.85	0.0
	Mean suburban Jan '12 lower bound 15m	6.39	6.39	6.39	6.39	6.39	0.0
	Jan 12 lower bound standard deviation	4		5.4		6	
	Mean suburban Jan '12 upper bound 1m	3.71	3.99	5.63	6	6.5	5.5
	Mean suburban Jan '12 upper bound 5m	6.29	6.86	10.17	10.9	11.92	11.0
	Mean suburban Jan '12 upper bound 10m	9.55	10.46	15.86	17.06	18.72	17.9
	Mean suburban Jan '12 upper bound 15m	12.79	14.06	21.54	23.2	25.5	24.8
	Jan 12 upper bound standard deviation	8		10.8		12	

The frequency exponent in this table is based on the difference between the loss values in the widest frequency range included in the assumptions, as follows:

$$\text{BPL frequency exponent (dB per decade)} = \frac{L_2 - L_1}{\log_{10}\left(\frac{f_2}{f_1}\right)}$$

The standard deviations of BPL for these publications are compared in Figure 4-6.

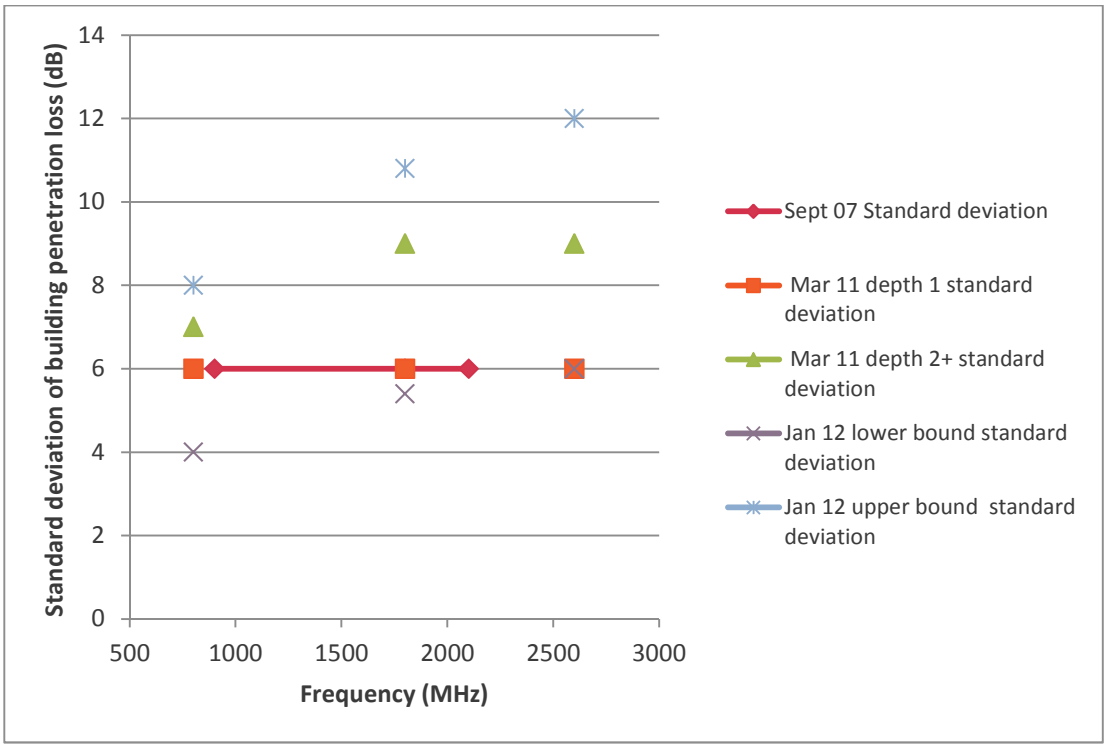


Figure 4-6: Comparison of BPL standard deviation assumptions used by Ofcom

5. Literature related to Building Penetration Loss

An extensive survey of literature related to Building Penetration Loss (BPL) has been conducted, where three key aspects have been considered, which are related to the dependency of BPL according to:

- Frequency
- Depth
- Type of buildings

The dependency of BPL and in general, the dependency of transmission loss with frequency, has been the study of researchers for many years. However, there are relatively few studies which measure using the same measurement approach across the range of frequencies of interest to Ofcom and over a large enough sample of buildings to be representative. This makes it difficult to compare directly between studies.

Each report has been examined and the most relevant parameters have been extracted. It should be noted that each study of building penetration loss tends to be approached in a different manner. Some studies look to derive theoretical models based on the physical properties of materials and then to tune these models using precise measurement data of individual building materials. Other studies are purely empirical, measuring a representative sample of real buildings and forming a conclusion from these. The latter are of more interest to the current study and have been prioritised here.

There is a great deal of variability in the approach as well as differences in the specific buildings examined. As a consequence of this, the spread of values of BPL arising from these studies is large. Some of the factors that will affect the outcome of BPL studies are for example:

- Cell type e.g. macro vs. micro.
- Building types e.g. office building vs. residential home.
- Building location e.g. isolated vs. built-up area.
- Penetration depth into building e.g. external wall or deep inside.
- Number of buildings surveyed
- Materials e.g. measured as an isolated sample or *in situ* as part of a wall or a building.

We have prioritised measured studies of whole buildings. Where possible the data has been separated by building type, e.g. between multi-storey offices and hotels typical of urban buildings and residential low-rise houses typical of suburban environments.

Research in this area consistently finds that propagation loss changes depending on the penetration depth inside the building. This is strongly related to the types of buildings and construction materials.

The most relevant results for BPL variation with frequency as well as with building types and depth into buildings are summarised in this section. A summary of all of the literature and the key numerical findings is provided in a table in Appendix 1.

5.1 Summary of findings

5.1.1 Qualcomm (2008)

A study carried out by Qualcomm [8] compares the path loss difference between UMTS900 and UMTS2100 in various environments, both outdoors and indoors. The indoor measurements involved 12 buildings, with measurements separated into two parts: first, the BPL between point A located just outside the building and point B located the other side of the external wall to point A and just inside the building; and then, the penetration loss inside the building, between point B just inside the building and point C much further into the building.

Qualcomm concluded that the average BPL at 2100MHz is 3.3 dB higher than that at 900MHz (12.8dB at 2100MHz compared to 9.5dB at 900MHz). However, the actual penetration loss varies substantially with the construction material and building geometry with their results showing a BPL at 900MHz as low as 2dB in some buildings but reaching 16dB in others.

This work also categorised the variation in BPL for different building types by the different building materials found in these building types and found the following variations:.

- Cement – 13 ~ 25 dB
- Mixture of glass, cement and brick - 4 ~ 15 dB
- Non-metallised glass - < 5dB

Despite these differences in the specific figures related to BPL, a general trend of an increase in loss with frequency was observed in most buildings (with the exception of Building 8). The trend in the mean BPL from 9.5 dB to 12.8 dB implies a frequency exponent of 9 dB/decade.

Regarding the indoor penetration testing, Qualcomm found that the signal at 900 MHz propagated better inside the building, for 10 tested buildings and when moving from the first wall to deep inside (B→ C). The average RSCP delta (BPL difference between 900 and 2100 MHz) was 1.8 dB higher at point B (just inside the buildings) than point A (outside the buildings) and rose by an additional 4 dB at point C (deeper inside the buildings).

The results from this study also indicate that the loss becomes greater when one moves deeper inside the building but reaches a maximum, at a certain depth. Physically this could be because the signal penetrating through an opposite wall becomes increasingly dominant. In some circumstances this could cause the loss to start to decrease with further depth depending on the geometry of the building relative to the surrounding cells.

5.1.2 Okamoto et al. (2009)

In [9], measurements were carried out over the frequency range 800 MHz to 8 GHz in 12 buildings (offices and hotels) and 5 multi-storey car parks in an urban area. The measurement results showed that the variation of loss with indoor penetration distance is 0.6 dB/m, which compares well with the parameters in the COST-231 model.

Regarding the frequency dependency of key parameters affecting the propagation loss, the first parameter analysed is the penetration distance coefficient. A tendency of the distance

penetration coefficient to increase with frequency was observed by the authors. Based on the results presented, if a linear regression analysis is performed on the measured data, a frequency coefficient of 0.1644 dB/decade for office buildings and 0.3421 dB/decade for the multi-storey car parks can be implied.

Regarding internal propagation losses (i.e. those measured from the basestation and an internal receiver), a variation very similar to that of free space loss (which would be 20 dB/decade) was seen with a result of 20.4dB/decade for multi-storey car parks and 18.3dB/decade for office buildings. Thus no additional dependency with frequency due to building penetration was observed.

It is worth noting that the distance between the base station and the building or the measured floor height was different for each building. The mean of the propagation losses in the office buildings or multi-storey car parks reported includes these differences. Therefore, the difference in the loss between the office buildings and the multi-storey car parks reported is relative. The average length of the measured courses in all rooms for all buildings was 8 metres with a standard deviation of 4 metres.

For the building penetration loss, a slight decrease in BPL with frequency was seen, which for office buildings had a frequency coefficient of -0.493 dB/decade and for multi-storey car parks was -0.361dB/decade.

5.1.3 T-Mobile Hungary (2009)

T-Mobile Hungary performed a test on individual building materials [10] indicating that BPL increases with frequency, as depicted in Table 5-1. It is of interest to note that the difference in BPL from 900 MHz to 2100 MHz (about 5dB) is significant for brick walls which may be especially relevant in the context of UK housing.

Table 5-1: BPL measurements performed by T-Mobile Hungary

Material	Loss at 900MHz / dB	Loss at 1800MHz / dB	Loss at 2100MHz / dB
Plexi 1 layer	0.8	0.9	0.9
Glass 1 layer	0.9	1.2	1.2
Plaster board 2 layers	4.5	6	6.5
Brick wall 19cm	7	11	12
Brick wall 30cm	8.5	14	14.5
Metal wapoured glass [sic]	18	25	28

Table 5-2: BPL losses according to depth ("daylight" = shallow) at 2100 MHz

	Daylight		Deep indoor	
	Mean / dB	**Standard deviation /dB**	**Mean / dB**	**Standard deviation / dB**
Downtown	12.7	4.9	19.9	4.9
Housing estate	3.9	4.4	8.9	3.8
Suburbs	8.2	3.7	17.8	3.6
Village	8.6	4.8	11.8	4.6

Greater depths lead to increased losses at 2100MHz as indicated in Table 5-2. It was found that the mobile position does not significantly influence the signal variability in these measurements.

5.1.4 Aguirre et al. (1994)

A study to quantify the viability of indoor coverage using street microcells was reported in [11]. Narrowband propagation measurements were performed for a total of 17 buildings, in the frequencies 912 MHz, 1920 MHz and 5990 MHz, to determine BPL figures. Seven houses made of brick and wood were tested: the remainder were multi-storey buildings made of concrete with large windows.

Results show that there is a general tendency for the mean and variability of BPL to increase with frequency for the two types of tested buildings. In all cases, although the distance between basestation and receiver positions was limited to 200 m in non-line of sight (NLOS) conditions, the authors report that zig-zag patterns were followed during the walk test, and that about 70% of the rooms could be measured, which implies that samples could be collected deep indoors.

For 900 MHz, the mean BPL for domestic housing buildings was 7.7 dB with a variability of 4 dB, whereas for multi-storey buildings the mean BPL was 12.5 dB (note that variability was not reported for multi-storey buildings).

At 1900 MHz, a mean BPL of 11.6 dB and a 7.3 dB variability was reported for domestic housing and a mean BPL of 15.5 dB for multi-storey buildings. Finally at 5990 MHz, a mean BPL of 16.1 dB for domestic housing with 8.7 dB variability and a 20 dB mean BPL for multi-storey buildings are reported.

Figure 5-1 shows a plot of the mean BPL vs. frequency found in this study and clearly shows an increase which depends on the specific materials, but it is very close to 10 dB/decade. The frequency coefficient for the variability in BPL loss is 5.53. dB/decade

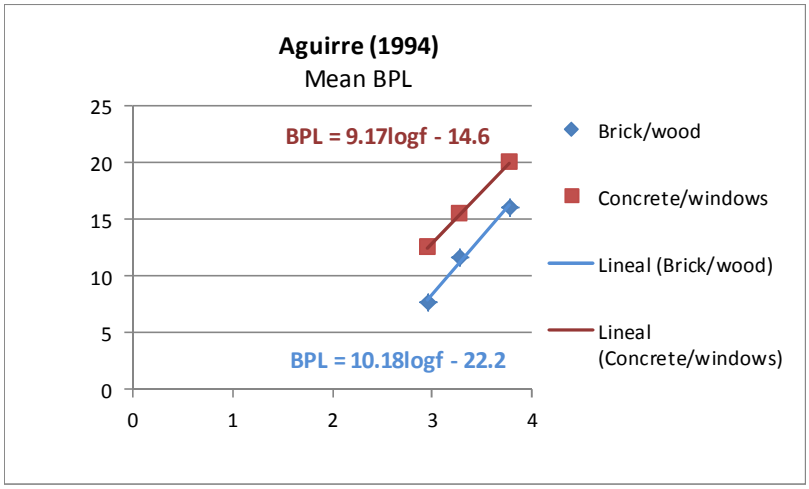


Figure 5-1: Mean BPL vs. frequency Aguirre et al. [11]

5.1.5 Bertoni et al. (1994)

A compilation of many references to date (1994) was made by [12], where key features of theoretical models and other factors affecting wireless propagation in the UHF band were analysed, including indoor, outdoor and outdoor-to-indoor scenarios. The BPL values researched and reported here are for 815 MHz and 914 MHz, and in both cases a 10 dB loss is mentioned, suggesting no changes in BPL with frequency were observed. Many references are cited in the paper, some of which are also discussed in this section.

5.1.6 Davidson and Hill (1997)

Measurements of BPL over 10 buildings at 900 MHz and 1500 MHz in Illinois, USA are reported in [13]. At 900 MHz, the mean BPL at ground floor level was found to be 10.8 dB with variability of 5.8 dB, whereas at 1500 MHz, the BPL was found to be 10.2 dB with a standard deviation of 5.6 dB. The slope of BPL decrease which is recommended by the authors and obtained from a best-fit curve is -7.9 dB/decade. A total of 10 buildings were measured, and the BPL was averaged over all these buildings. There was a mixture of office buildings and hotels in the survey, made of concrete and glass windows.

5.1.7 De Backer et al. (1996)

The effect of windows on BPL has been studied in [14], where BPL measurements are reported for a wall with and without window, at 1800 MHz. The measurements were performed on a building with brick walls, covered by a thin layer of concrete on the inside. In the middle of the wall, a 3-plate glass window was fitted in a frame of wood and aluminium.

The results reported by the authors clearly demonstrate the large impact of windows in the transmission loss. As quoted by the authors: “The mean level with the window closed is 15.4 dB below free space (on average). When the window is opened the level is increased to 1.9 dB below free space (again on average). This situation would of course have been quite different if a two or one plate window had been studied, or if the reflectivity of the window had been lower”. This suggests that metallised windows as used in many modern office buildings may have a significant impact on BPL.

5.1.8 De Toledo and Turkmani (1992)

Investigations of propagation into, and within buildings were conducted at 900, 1800 and 2300 MHz in Liverpool, UK by [15]. The average measured BPL at ground floor level was found to be 14.2, 13.4 and 12.8 dB respectively for 900, 800 and 2300 MHz, measuring everywhere within the building. The standard deviation of such measurements was 8.09, 7.6 and 7.56 dB, respectively. The type of building measured was an office block, at the University of Liverpool campus, including classrooms, offices and labs, made of reinforced concrete and large windows. In all cases, a decrease in BPL and variability with frequency was observed, having a frequency coefficient of -3.27 dB/decade for the mean BPL and -1.37 dB/decade for the standard deviation of the BPL.

The path loss exponent for measurements inside the building increased with frequency, reporting values of 5.3, 5.5 and 6.0 respectively for 900, 1800 and 2300 MHz, which

suggests an increase in indoor propagation loss deeper in the building with an increase in frequency.

5.1.9 Ferreira et al. (2006)

A study of the extra signal attenuation due to building penetration associated to path loss for different types of buildings and rooms in Lisbon and Porto, Portugal is reported in [16] for GSM (900 and 1800 MHz) and UMTS (2100 MHz). A heterogeneous set of 12 buildings was selected for the measurements, classified as:

- High-integrated (HIn): building with more than 6 floors, sharing walls with other buildings (2 measured buildings)
- High-isolated (HIs): building with more than 6 floors, not sharing any walls with other buildings (4 measured buildings)
- Low-integrated (LIn): a building up to 6 floors, sharing walls with other buildings (3 measured buildings)
- Low-isolated (LIs): a building up to 6 floors, not sharing any walls with other buildings (3 measured buildings)

Also, a total of 434 rooms with distinct characteristics were measured, according to three different categories:

- Indoor light (IL): a room with a window to outdoors (303 rooms measured)
- Indoor (I): a room without any window to outdoors, but one wall separation to outdoors (73 rooms measured)
- Deep indoor (DI): a room without any window to outdoors, and with at least two walls separation to outdoors (58 rooms measured)

In order to understand the differences in BPL amongst all the described types of buildings and rooms, Table 5-3 shows the global results for average μ and standard deviation σ for GSM900. It can be seen that the BPL changes substantially between building types, but also increases with the penetration depth.

Table 5-3: Mean and standard deviation values for the BPL from Ferreira et al. (2006)

	Deep Indoor		Indoor		Indoor Light		Average per building type	
	Mean/dB	Std. dev./dB	Mean/dB	Std. dev./dB	Mean/dB	Std. dev./dB	Mean/dB	Std. dev./dB
HIn	8.8	8.9	7.2	9.3	4.5	9.4	5.6	9.5
HIs	5.8	11.5	2.0	11.7	1.2	10.1	2.0	10.8
LIn	12.3	11.5	6.2	12.9	5.5	12.9	5.8	13.1
LIs	12.3	12.2	9.0	9.0	8.3	11.2	9.1	11.2
Average per room type	9.7	11.1	4.8	11.0	5.0	10.9	5.7	11.1

When the three frequency bands are analysed, a mean BPL of 5.7 dB with a standard deviation of 10.8 dB is reported for 900 MHz; for 1800 MHz, a mean BPL of 7.6 dB is indicated with a variability of 12 dB; and finally, for 2100 MHz, a mean BPL of 7.3 dB with a standard deviation of 12.5 dB is reported. Note that this shows an increase in BPL with frequency, especially from 900 MHz to 1800 MHz. In the case of the 2100 MHz result there is a slight decrease from 1800MHz which may be within the measurement error. Overall, the increase in BPL yields a frequency coefficient of 4.95 dB/decade for the mean BPL, and 4.43 dB/decade for the BPL standard deviation.

Ferreira et al. recommend attenuation values for penetration into buildings to be considered for different percentiles of coverage. To provide 95% coverage inside buildings, an extra attenuation factor of 18.5 dB has to be considered for GSM900 and 20.4 dB for GSM1800.

Finally, the authors conclude that attenuation due to penetration into buildings increases as one goes "deeper into the building" as follows: 5 dB to indoor light, and 9 dB to deep indoor, on average.

5.1.10 Gahleitner and Bonek (1994)

In [17], measurements at 950 MHz and 1850 MHz were conducted into various urban buildings in Vienna, Austria. Three office blocks and multi-storey buildings were measured, made of different construction materials.

For brick, a BPL of 14.3 dB is reported at 950 MHz, whereas 16.4 dB is indicated at 1800 MHz. For brick and concrete, 22 dB is reported for 950 MHz, and 22.3 dB at 1800 MHz. Finally, for reinforced concrete, a mean BPL of 18 dB is reported, and 20.1 dB is shown at 1800 MHz. In all cases, a variability of BPL of 3 to 6 dB is reported. For brick constructions the BPL increased more with frequency but such an increase was not so predominant if concrete was present.

In all cases, a tendency of the penetration loss to increase with frequency is observed, yielding an overall frequency coefficient of 5.4 dB/decade.

5.1.11 Ofcom project SES-2005-08 (2007)

In [18], theoretical predictions were conducted at four different frequencies (1000 MHz, 2000 MHz, 5 GHz and 10 GHz) used in conjunction with urban building models, from which BPL values are suggested for these frequency bands. Five office buildings have been simulated, for which mean BPL values of 11.32 dB, 12.64 dB, 16.6 dB and 23.2 dB are reported, respectively, for 1 GHz, 2 GHz, 5 GHz and 10 GHz frequency bands. The simulations show that as the frequency increases so too does the mean BPL yielding a frequency coefficient of $11.6 \log f_{MHz}$.

In addition to the above mentioned report, a technical note was delivered within this project [19], for which simple frequency-dependent models for the relative permittivity and conductivity of a number of building materials are presented. The models are based on the collation of a number of published measurement results, mainly in the frequency range 1–100 GHz, to use for indoor-outdoor ray tracing propagation modelling. A large variety of materials were tested, including concrete, brick, plasterboard, wood, glass, ceiling board, chipboard, miscellaneous board and stone material and ground. Simple expressions for the frequency dependence of the relative permittivity, $\varepsilon_r^{'}$, and the conductivity, σ, were derived. These are:

$$\varepsilon_r = a f_{GHz}^{b}$$

and

$$\sigma = c f_{GHz}^{d}$$

where f_{GHz} is the frequency in GHz and σ is in S/m. ($\varepsilon_r^{'}$ is dimensionless.) The values of *a*, *b*, *c* and *d* are given in Table 5-4. Where the value of *b* or *d* is absent, this indicates that the value of $\varepsilon_r^{'}$ or σ is constant (with value *a* or *c*) independent of frequency. This is equivalent to setting the value of *b* or *d* to zero.

Since BPL is related to transmission loss, this loss depends on the constitutive parameters (permittivity, conductivity and permeability) of the wall materials. The amount of transmitted and reflected energy can be computed from the so-called *Fresnel transmission and reflection coefficients* [20], which also depend on the angle of incidence of the incoming rays as well as the intrinsic impedances – and these impedances vary as the constitutive parameters also vary with frequency.

Table 5-4: Model parameters from technical note [19]

Material class	Relative permittivity		Conductivity		Frequency range
	a	*b*	*c*	*d*	GHz
Concrete	5.31		0.0326	0.8095	1–100
Brick	3.75		0.038		1–10
Plasterboard	2.94		0.0116	0.7076	1–100
Wood	1.99		0.0047	1.0718	0.001–100
Glass	5.35		0.0043	1.1381	1–100
Ceiling board	1.50		0.0005	1.1634	1–100
Chipboard	2.94		0.0569	0.5413	1–100
Very dry ground	3		0.00015	2.52	1–10 only
Medium dry ground	15	–0.1	0.035	1.63	1–10 only
Wet ground	30	–0.4	0.15	1.30	1–10 only

5.1.12 ITU-R P.1238-3 (2003)

The ITU-R has published a set of recommended values of penetration loss with frequency [21], for the 900 MHz, 1900 MHz and 5200 MHz frequency bands, obtained from measurements in five urban office buildings, for which the specific construction materials are not specified. Mean BPL values of 9 dB, 15 dB and 16 dB are reported respectively for 900, 1900 and 5200 MHz. Again, an increase in BPL with frequency is observed, being larger below 2 GHz and less pronounced beyond this up to 5 GHz. The frequency coefficient for the mean BPL is 8.8 dB/decade.

5.1.13 Tanis and Pilato (1993)

Eleven buildings in an urban area were measured at 880 MHz and 1922 MHz to obtain building penetration characteristics for Personal Communications Service (PCS) systems, as reported in [22], in Philadelphia, USA. The tests were conducted in urban, suburban and semi-rural environments, including two malls, a multi-storey hotel and a high-rise office complex. BPL averaged 19.2 dB for 880 MHz and 15.7 dB for 1922 MHz. The reported variability was smaller for 1922 MHz.

Results from this work show that at 1922 MHz 3.5 dB less penetration loss was encountered than at 880 MHz. Such a reduction in penetration loss at higher frequencies reveals a sort of “frequency selective” behaviour, according to the authors, which is strongly related to the complexity of building materials of the building walls. In fact, the frequency coefficient for this scenario has a negative slope, suggesting a decrease in BPL, of −10.3 dB/decade.

5.1.14 Turkmani at al. (1988)

Another interesting scenario where the BPL has been reported to decrease with frequency is reported in [23], whose results are in line with other papers published by Turkmani regarding BPL. The measured frequencies in this study were 441 MHz, 900 MHz and 1400 MHz in four office block buildings within the University of Liverpool campus, made of concrete and glass windows. Mean BPL values of 16.37 dB, 11.61 dB and 7.56 dB were reported, respectively, showing a decrease expressed by a frequency coefficient of -17.35.dB/decade. Details of the variability are not given.

5.1.15 Wells (1977)

In [24], the results of a measurement programme conducted to determine the attenuation at UHF of radio signals penetrating to the inside of a typical house is presented. Six houses were measured, made of wood and brick, and across 13 rooms in total. BPL values of 5.5 dB, 6.7 dB and 7.5 dB respectively are reported for 860 MHz, 1550 MHz and 2569 MHz. A slight increase in BPL with frequency is reported, having a frequency coefficient of 4.22 dB/decade.

5.1.16 Xavier et al. (2003)

As part of the European project COST-273, measurements to characterise signal penetration into buildings for GSM were performed [25] for 11 office buildings in the city of Lisbon, Portugal, at 1800 MHz. The buildings were constructed mainly of glass, brick and concrete. High-isolated buildings differentiate themselves from all others, showing that sharing walls between buildings also has an impact on the BPL. The window sizes in all cases ranged from medium to large, and the average thickness of the penetrated walls was 30 cm.

The mean BPL reported by the authors is 10.2 dB with a standard deviation of 13.8 dB, obtained by averaging the individual BPL values for all buildings. Measurements were conducted everywhere inside the buildings.

5.1.17 Devasirvatham (1994)

The work reported by [26] is often referenced in other relevant literature related to penetration losses. From measurements conducted at 850 MHz, BPL is calculated and extended to 1900 MHz for PCS cellular systems. The measurements were performed over house-type buildings, made of brick and concrete. The results show a reduction in median received signal strength at 1900 MHz of 15 dB for similar transmitter conditions at 850 MHz, which suggests a frequency coefficient for mean BPL of 42.9 dB/decade, although this appears to be for the total path loss rather than the BPL. There is also an increase in variability of the BPL of 10% from 850 MHz to 1900 MHz, corresponding to a frequency coefficient for the variability in BPL of 2.29 dB/decade.

5.1.18 Celik et al. (2011)

In [27], the dependency of the propagation loss with depth at various frequencies is reported. The transmitter was located indoors, whereas various samples were collected around a university campus building. Therefore, for small distances, the external penetration wall loss was estimated, since no additional walls were encountered. For other cases, the BPL was added to the losses due to the internal walls. The authors account for the effects of frequency dependence by considering a frequency factor (frequency f is in GHz):

$$L(f) = 10.81\sqrt{f} - 9.51$$

The results from their observations , show that their model, which is based on COST-231 NLOS model, performs quite well using the values suggested by COST-231 ($W_e = 7$; $W_{ge} = 6$ for 900 MHz and =7 for 1800 and 2100 MHz; $\alpha = 0.6$ dB/m; $W_i = 7$) for 900 MHz, 1800 MHz and 2100 MHz, and that loss also varies with the depth depending on the specific measurement scenario. In all cases, the authors suggest an increase in BPL with frequency. However, the measurement results presented show little apparent difference between 900 and 1800 MHz.

5.1.19 Chee et al. (2011)

In [28], the authors have performed measurements for broadband wireless access on 7 residential buildings at 850 MHz, and on 4 residential buildings at 3500 MHz. Data recording on the latter ones was performed simultaneously at both frequencies, to establish a more clear comparison. Measurements on the ground floor could be collected in all the areas of the houses, whereas the upper floor measurements were more restricted.

A very slight increase in BPL with frequency is observed, going from 11.4 dB at 850 MHz to 13.3 dB at 3500 MHz (frequency coefficient of 2.63 dB/decade) despite the large increase in frequency. The BPL thus was found to exhibit weak frequency dependency. It is worth pointing out that all measurements were performed at close proximity (1 m away) from the walls, and that a distance-dependent factor of 0.6 dB/m was considered.

5.1.20 Medbo et al. (2009)

The authors in [29] performed a series of measurements in 5 office buildings in Stockholm, Sweden, and reported a slight decrease in excess building loss from 460 MHz to 881 MHz, and then some increase from 1860 MHz to 5100 MHz. The median BPL values are: 22 dB, 19.3 dB, 22 dB and 24 dB respectively for 460 MHz, 881 MHz, 1859 MHz and 5100 MHz. Overall, if all the mean BPL values are considered for the entire frequency range, a frequency coefficient of 2.745 dB/decade is obtained.

In summary, the study shows that frequency dependencies may or may not occur in different propagation environments and scenarios. In particular, the authors again refer to the effects of metallised walls in some of the building results as follows:

“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 LOS condition. The resulting shielding loss of the exterior wall is 12, 16, 16 and 22 dB at carrier frequencies 460, 880, 1860 and 5100 MHz respectively".

5.1.21 LaSorte et al. (2009)

Other types of buildings have also been characterised for building penetration losses. This is the case of hospitals in [30], where measurements were conducted from 55 MHz to 1950 MHz in St. Francis Hospital, Tulsa, Oklahoma, USA. This hospital is constructed with special walls that include metallic layers. Corridors on each of the tested floors were most favoured as walk routes, although some MRT and X-ray rooms were included. A number of samples were collected as well around the outside perimeter of the hospital building. The exterior walls of the hospital were made of concrete.

The reported BPL values ranged from 25dB to 16dB depending on the measurement frequency. At low frequencies, the BPL appeared to increase and decrease depending on the frequency intervals. However, as the measurement frequency increased beyond 900 MHz, the tendency of the BPL was to decrease with frequency.

5.1.22 Stone (1997)

Although this survey focuses more on measurements of complete buildings rather than of material samples in isolation, Stone [31] provides a particularly thorough set of measurements, which examines attenuation through many different types of construction materials in the frequency range 0.5 to 2.1GHz and 3 to 8 GHz and finds a general increase in loss. This trend is to be expected, as the skin depth is least at the highest frequencies, so the current density is greatest at the highest frequencies and the losses arising from conversion from electromagnetic to thermal energy are greater.

5.1.23 Virginia Polytechnic (2002)

In line with the characterisation of construction building materials in the lab, the authors in [32] performed a series of measurements in the range 1 to 15 GHz for various construction materials, including: drywall, wall board, structure wood, glass sheet, bricks, concrete blocks, reinforced concrete, cloth office partition, wooden door and styrofoam slab.

Results show that whereas the dielectric constant does not vary significantly with frequency, the attenuation constant does increase substantially as the frequency increases. This is something that was expected and reaffirms other measurements performed on materials in isolation.

5.1.24 Wilson (2002)

Another relevant study was reported in [33], where twenty materials, both homogeneous and composite, have been studied to determine the variation in transmitted and reflected energy over frequency. In order to verify the observed behaviour, the measured data was used to calculate the relative permittivity and loss tangent of each material and the observed behaviour compared to that of a common plane-parallel plate physical model.

For most materials, the decrease in received power between 2.3 and 5.25 GHz is less than 1 dB, the exceptions being red brick (10.1 dB), glass (1.2 dB), Fir lumber (3.3 dB), cinder block (3.6 dB) and stucco (increased 1.6 dB). The reflected energy also shows a strong frequency dependence that is a function of the thickness of the sample, as well as its permittivity.

5.1.25 Martjin and Herben (2003)

Measurements over four office block buildings were conducted at 1800 MHz in the Netherlands [34]. The buildings were made of concrete and brick, and quite different mean BPL values were obtained: 13 dB, 5 dB, 4 dB and 12 dB, the last one for brick construction. The reported standard deviations are 2 dB, 4 dB, 7 dB and 4 dB, respectively, for the four measured buildings. Large fluctuations are observed between signal levels received in different parts of the building.

5.1.26 CRC Canada (2011)

Frequency-dependent features of signal transmission performance in several radio propagation environments are evaluated in [35], with special interest in the frequency bands of 700 MHz and 2500 MHz. The objective of this study was to analyse technical aspects of propagation behaviour in cluttered environments, for which an extensive analysis and literature search was performed. The following remarks related to BPL can be made from this work:

- Based on empirical results, for residential buildings, BPL increases with frequency, being 3.9 dB lower at 700 MHz than at 2500 MHz.
- On the other hand, for industrial and commercial environments, average BPL values are estimated to be 4.3 dB higher at 700 MHz, thus decreasing indoor coverage performance with respect to 2500 MHz.

5.1.27 Dalke et al. (2000)

In [36], measurements from 100 MHz to 6 GHz are performed to determine the transmission and reflection coefficients for reinforced concrete walls, having a well-defined rebar (reinforcing bar, as commonly used in the reinforcement of concrete) lattice configuration.

Results show that at low frequencies, the transmitted signal is attenuated by the rebar structure. As the frequency increases, the effects of the wall become more pronounced and result in larger than expected transmission coefficients. These results show that the transmission coefficient for the reinforced wall can be much larger than what would be predicted for a rebar structure alone. Also, the authors quote that as the frequency increases, the transmission and reflection coefficients vary significantly. The authors therefore suggest: “from a communication system designer’s point of view, a 20 to 30 dB link margin may be needed to obtain the required signal-to-noise ratio when the signal penetrates such reinforced concrete structures”.

As stated earlier, the fact that the transmission and reflection coefficients in practice vary with frequency, is a clear indication that the BPL will also have a dependency on frequency.

5.1.28 Gibson and Jenn (1999)

A propagation loss study is presented in [37] to determine the attenuation of various building walls. The transmission between two identical antennas at a fixed spacing was measured to establish a reference. Then the antennas were placed on opposite sides of the wall under test such that the spacing was the same as for the reference measurement. A comparison of the two received powers gives an estimate of the wall insertion loss. The range of frequencies at which the measurements were performed is from 2 GHz to 6 GHz.

Three materials were tested: concrete, wood door and metal door, for which the results indicate an increase in BPL as the frequency also increases. These results indicate that the frequency coefficient for concrete is 27 dB/decade and for wood it is 9.4 dB/decade.

5.1.29 Hoppe et al. (1999)

Reference [38] reports measurements performed along four university campus buildings at the University of Stuttgart, Germany, at 230 MHz and 1500 MHz. The walk routes covered both corridors and offices in all buildings.

Results show that the mean BPL increased with frequency, having a frequency coefficient of 3.52 dB/decade whereas the standard deviation decreases with frequency, with a frequency coefficient of −2.9 dB/decade.

5.2 Summary of references

5.2.1 Compiled list of references

See Appendix 1 for a full list of the references treated in this section, which extracts the key BPL-related parameters for each.

5.2.2 BPL values from literature

The BPL values from all of the literature reported here are graphed in Figure 5-2 (other results are available above 3 GHz).

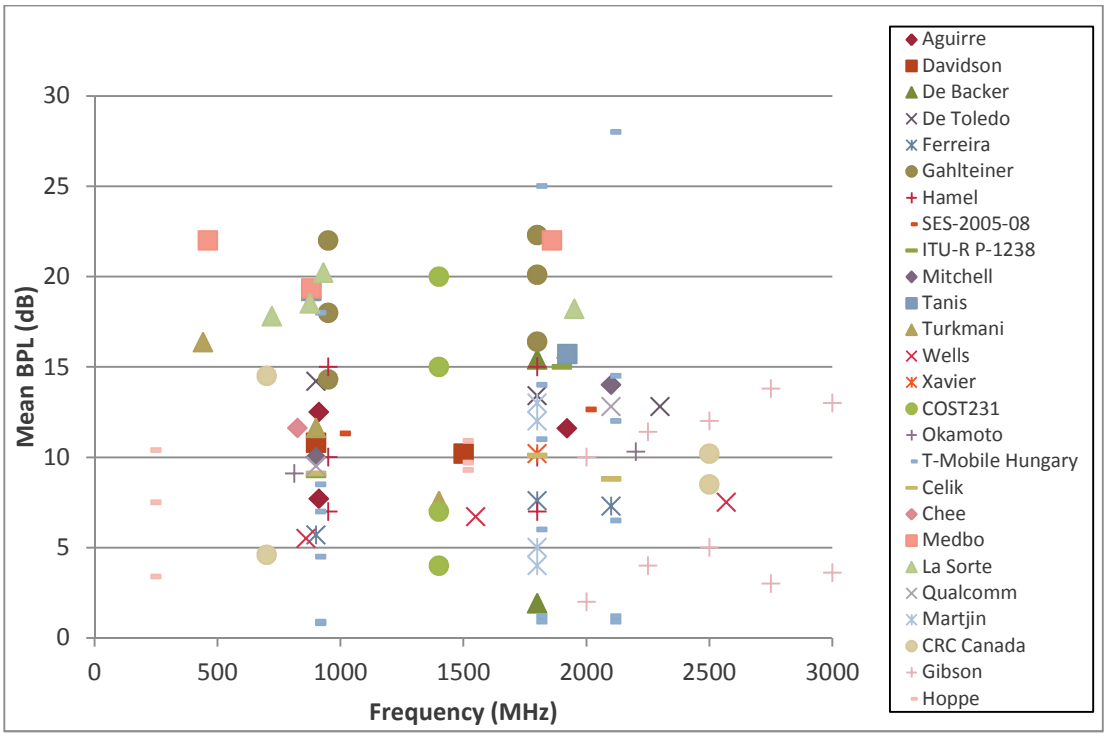


Figure 5-2: Mean BPL values from literature versus frequency

The values specifically relating to suburban residential environments and to urban multi-storey buildings are shown in Figure 5-3 and Figure 5-4, with the corresponding assumptions from the January 2012 consultation also shown for comparison.

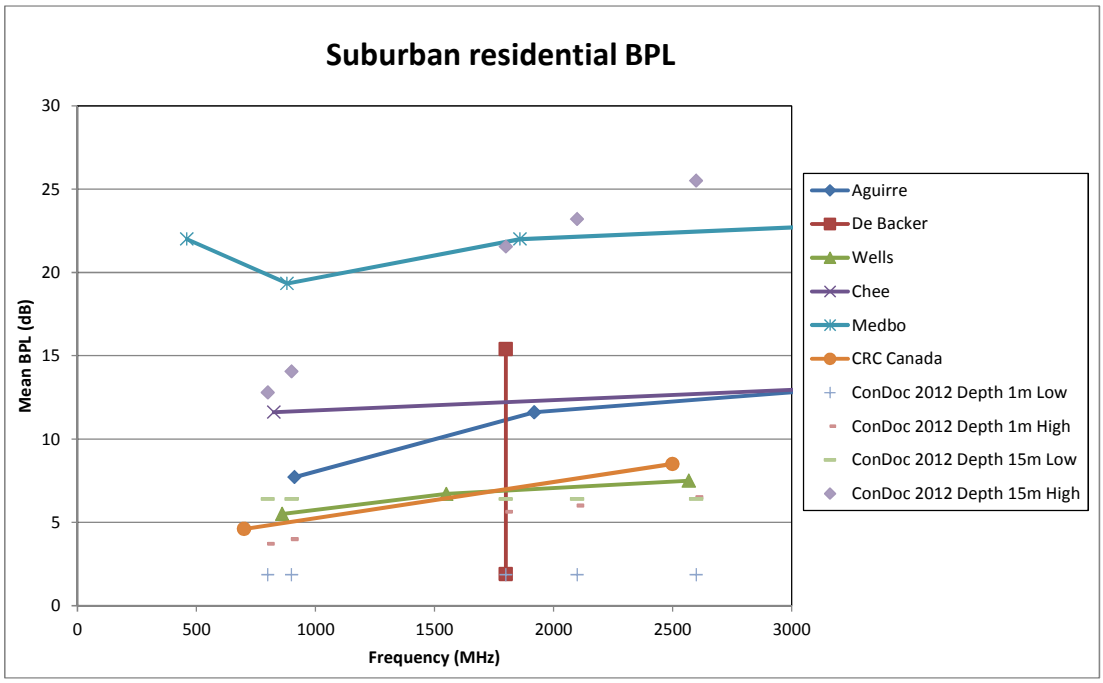


Figure 5-3: Mean BPL values for suburban residential buildings from literature and from January 2012 consultation

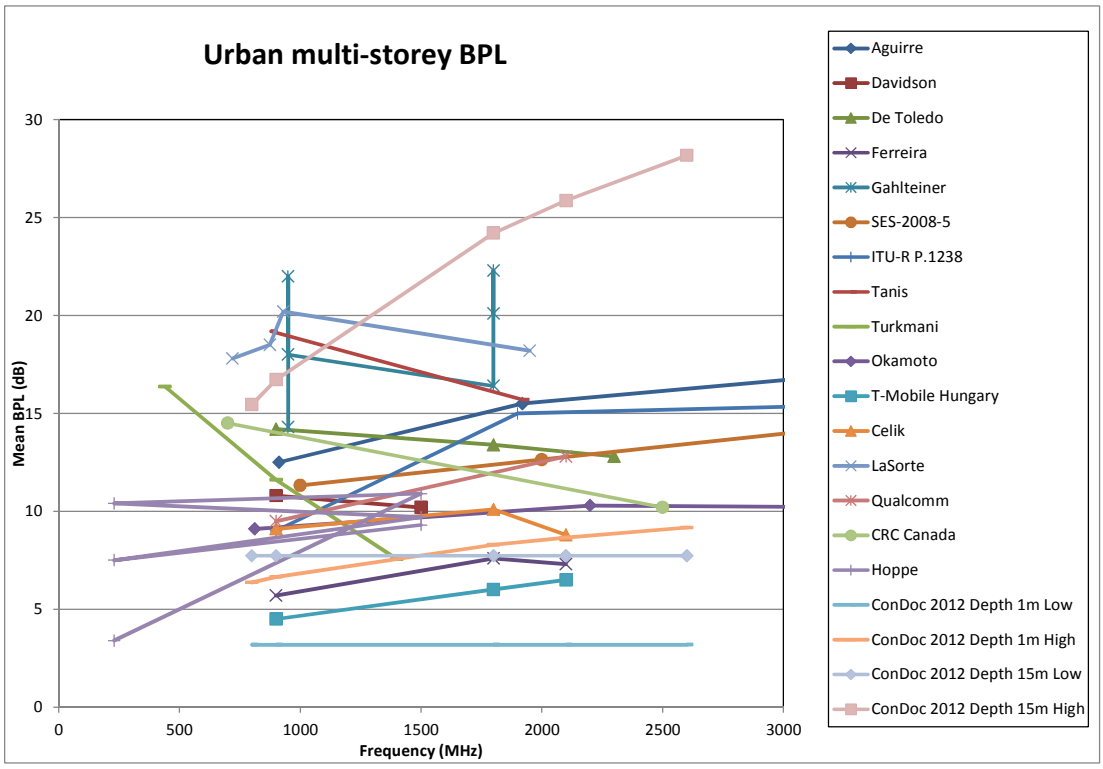


Figure 5-4: Mean BPL values for urban multi-storey buildings from literature and from January 2012 consultation

5.2.3 Frequency coefficient variation

A summary of the frequency coefficient variation as reported by all the listed authors is shown in Figure 5-5 below. It can be seen that although some authors report a decrease in BPL with frequency, most of the references quote an increase (resulting in a positive frequency coefficient), even if this value is only slightly greater than zero as is the case of Okamoto (2009) and Celik (2011). Other authors, such as Qualcomm and Aguirre show dependencies as high as around 10 dB/decade. While some of these differences may result from methodological issues, it seems clear that there is substantial genuine variation in frequency dependency (as well as absolute penetration loss) amongst individual buildings, as expected on physical grounds.

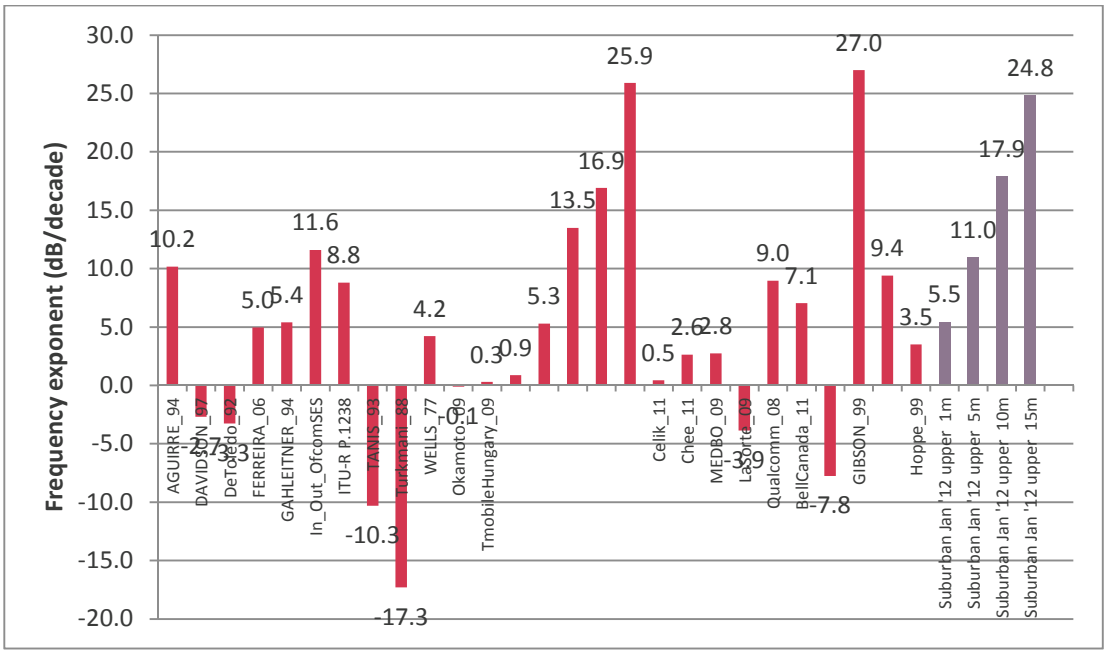


Figure 5-5: Summary of frequency coefficient variation as reported in the literature, compared with January 2012 consultation (suburban, upper bound) assumptions

6. Appendix 1: Summary of references

The most relevant selected references are included here as a table, with the main characteristics listed on each case.

Reference	Frequency [MHz]	Theory / Measured	No. Buildings	Building type	Building materials	Depth [m]	Mean BPL [dB]	Variability [dB]	Frequency coefficient	Comments / remarks
Aguirre, [11]	912	Measured	7	House	Brick / wood	Deep indoors	7.7	4.0	10.18	Microcells, BPL increases with frequency in all cases
	1920	Measured	7	House	Brick / wood	Deep indoors	11.6	7.3	10.18	
	5990	Measured	7	House	Brick / wood	Deep indoors	16.1	8.7	10.18	
	912	Measured	4	Multi-storey	Concrete + windows	Deep indoors	12.5	Not given	9.17	
	1920	Measured	4	Multi-storey	Concrete + windows	Deep indoors	15.5	Not given	9.17	
	5990	Measured	4	Multi-storey	Concrete + windows	Deep indoors	20	Not given	9.17	
Bertoni, [12]	815	Research			Concrete floor		10	Not given	0	Compilation of other authors references and work
	914	Research			Concrete floor		10	Not given	0	
Davidson, [13]	900	Measured	10	Offices + hotels	Concrete + glass windows	Deep indoors	10.8	5.8	-2.7	BPL slightly decreases with frequency, as well as the variability
	1500	Measured	10	Offices + hotels	Concrete + glass windows	Deep indoors	10.2	5.6	-2.7	
De_Backer, [14]	1800	Measured	1		Windowed brick wall (opened)	Shallow	1.9	Not given	N/A	Significant increase in the BPL with closed windows
	1800	Measured	1		Windowed brick wall (closed)	Shallow	15.4	Not given	N/A	
DeToledo, [15]	900	Measured	1	Office block	Reinforced concrete + large windows	Everywhere	14.2	8.09	-3.26	Decrease in std dev as frequency increases; BPL decrease as the frequency increases
	1800	Measured	1	Office block	Reinforced concrete + large windows	Everywhere	13.4	7.6	-3.26	
	2300	Measured	1	Office block	Reinforced concrete + large windows	Everywhere	12.8	7.56	-3.26	
Ferreira, [16]	900	Measured	12	Multi-storey	Not specified	Everywhere	5.7	10.8	4.95	Variable tendency,

	1800	Measured	12	Multi-storey	Not specified	Everywhere	7.6	12	4.95	although can be said that in general BPL increases with frequency
	2100	Measured	12	Multi-storey	Not specified	Everywhere	7.3	12.5	4.95	
Gahleitner, [17]	950	Measured	3	Offices, multi-storey	Brick	Deep indoors	14.3	3-6	5.4	Ground floor measurements, there is an increase in BPL in all cases with the frequency, which is less pronounced for the second building (brick and porous concrete)
	950	Measured	3	Offices, multi-storey	Brick + concrete	Deep indoors	22	3-6	5.4	
	950	Measured	3	Offices, multi-storey	Reinforced concrete	Deep indoors	18	3-6	5.4	
	1800	Measured	3	Offices, multi-storey	Brick	Deep indoors	16.4	3-6	5.4	
	1800	Measured	3	Offices, multi-storey	Brick + concrete	Deep indoors	22.3	3-6	5.4	
	1800	Measured	3	Offices, multi-storey	Reinforced concrete	Deep indoors	20.1	3-6	5.4	
Hamel, [39]	950	Theory	3	N/A	Urban		15	10	0	Decrease in BPL but increase in variability with frequency. Quoted by some references as the "industry standard"
	950	Theory	3	N/A	Suburban		10	10	0	
	950	Theory	3	N/A	Corridor		7	10	0	
	1800	Theory	3	N/A	Urban		15	12	0	
	1800	Theory	3	N/A	Suburban		10	12	0	
	1800	Theory	3	N/A	Corridor		7	12	0	
In_Out_OfcomSES, [18]	1000	Theory	5	Urban offices	N/A		11.32	Not given	11.6	General increase of BPL with frequency
	2000	Theory	5	Urban offices	N/A		12.64	Not given	11.6	
	5000	Theory	5	Urban offices	N/A		16.6	Not given	11.6	
	10000	Theory	5	Urban offices	N/A		23.2	Not given	11.6	
ITU-R P.1238, [21]	900	Measured	5	Urban offices	N/A	Not specified	9	Not given	8.8	Based on measurements
	1900	Measured	5	Urban offices	N/A	Not specified	15	Not given	8.8	
	5200	Measured	5	Urban offices	N/A	Not specified	16	Not given	8.8	
Mitchell, [40]	900	Research			General		10	6	10.87	Not measured; derived from experience and literature
	2100	Research			General		14	6	10.87	

Tanis, [22]	880	Measured	11	Urban	N/A	Deep indoors	19.2	Not given	-10.3	Decrease in frequency
	1922	Measured	11	Urban	N/A	Deep indoors	15.7	Not given	-10.3	
Turkmani, [23]	441	Measured	4	Office block	Concrete + windows	Everywhere	16.37	Not given	-17.3	BPL is reported to decrease as frequency increases
	900	Measured	4	Office block	Concrete + windows	Everywhere	11.61	Not given	-17.3	
	1400	Measured	4	Office block	Concrete + windows	Everywhere	7.56	Not given	-17.3	
Wells, [24]	860	Measured	6	House	Wood / brick	Everywhere	5.5	Not given	4.22	13 rooms
	1550	Measured	6	House	Wood / brick	Everywhere	6.7	Not given	4.22	
	2569	Measured	6	House	Wood / brick	Everywhere	7.5	Not given	4.22	
Xavier, [25]	1800	Measured	11	Offices	Glass + brick + concrete	Everywhere	10.2	13.8	N/A	Single frequency, reported BPL for 1800 MHz
Cichon, [41]	1400	Measured		N/A	Concrete	Not specified	15	10 ... 20	N/A	Data obtained from other references
	1400	Measured		N/A	Concrete + window	Not specified	7		N/A	
	1400	Measured		N/A	Wood	Not specified	4		N/A	
	1400	Measured		N/A	Floor (4 ... 37)	Not specified	20	5 ... 15	N/A	
Devasirvatham, [26]	850	Measured	8	House	Concrete + windows	Everywhere	See comments	See comments	42.9	The paper only reports an increase of 15 dB of BPL when the frequency increases from 850 MHz to 1900 MHz. The variability also shows an increase of 10%
	1900	Theory		House	Concrete + windows	Everywhere			42.9	
Ichitsubo, [9]	812	Measured	17	Offices + hotels + multi-storey car parks	Reinforced concrete with 1 window	Deep indoors	9.1	Not given	-0.12	No frequency dependency is reported by the authors for the range they tested. It also confirms the 0.6 dB/km of distance attenuation with depth proposed by COST-231
	2200	Measured					10.3	Not given	-0.12	
	4700	Measured					10.1	Not given	-0.12	
	8450	Measured					8.8	Not given	-0.12	
TMobile Hungary, [10]	900	Measured	3	Multi-storey	Plexi 1 layer	Deep indoors	0.8	Not given	0.29	All materials show a dependency with frequency, resulting in an increase
					Glass 1 layer	Deep indoors	0.9	Not given	0.87	

					Plaster board 2 layers	Deep indoors	4.5	Not given	5.3	in BPL as the frequency increases. The rates of increase, given by the frequency coefficients, vary depending on specific properties of the materials.
					Brick wall 19cm	Deep indoors	7	Not given	13.49	
					Brick wall 30cm	Deep indoors	8.5	Not given	16.9	
					Metal wapoured glass	Deep indoors	18	Not given	25.9	
	1800	Measured	3	Multi-storey	Plexi 1 layer	Deep indoors	0.9	Not given	0.29	
					Glass 1 layer	Deep indoors	1.2	Not given	0.87	
					Plaster board 2 layers	Deep indoors	6	Not given	5.3	
					Brick wall 19cm	Deep indoors	11	Not given	13.49	
					Brick wall 30cm	Deep indoors	14	Not given	16.9	
					Metal wapoured glass	Deep indoors	25	Not given	25.9	
	2100	Measured	3	Multi-storey	Plexi 1 layer	Deep indoors	0.9	Not given	0.29	
					Glass 1 layer	Deep indoors	1.2	Not given	0.87	
					Plaster board 2 layers	Deep indoors	6.5	Not given	5.3	
					Brick wall 19cm	Deep indoors	12	Not given	13.49	
					Brick wall 30cm	Deep indoors	14.5	Not given	16.9	
					Metal wapoured glass	Deep indoors	28	Not given	25.9	
Celik, [27]	900	Measured	1	University campus building	Concrete + plaster walls	Deep indoors	9.1	Not given	0.45	A slight increase in propagation loss is observed as the frequency increases, especially for the 2100 MHz band.
	1800	Measured					10.1	Not given	0.45	
	2100	Measured					8.8	Not given	0.45	

Chee, [28]	825	Measured	7	Residential	Not specified	Shallow	11.6	Not given	2.63	BPL was concluded to have no change with frequency.
	3500	Measured	4				13.3	Not given	2.63	
Medbo, [29]	460	Measured	5	Offices and residential	Not specified	Everywhere	22	Not given	2.75	The PBL is not dependent on frequency, despite a small decrease from 460 MHz to 880 MHz, and then an increase from 1860 MHz to 5100 MHz.
	881	Measured					19.3	Not given	2.75	
	1859	Measured					22	Not given	2.75	
	5100	Measured					24	Not given	2.75	
LaSorte, [30]	720	Measured	1	Hospital	Concrete	Everywhere	17.8	Not given	-3.87	The trend does not show a clear increase or decrease in PBL with frequency.
	875	Measured					18.5	Not given	-3.87	
	930	Measured					20.2	Not given	-3.87	
	1950	Measured					18.2	Not given	-3.87	
Qualcomm, [8]	900	Measured	12	Offices	Glass, brick, cement buildings	Everywhere	9.5	Not given	8.97	Increase of BPL with frequency, and also better performance of 900 MHz as it penetrates more the building (depth)
	2100	Measured	12				12.8	Not given	8.97	
Stone, [31]	0.5 GHz to 2.1 GHz and 3 to 8 GHz	Measured			Brick, masonry block, concrete, glass, plywood, lumber, dry wall, reinforced concrete, steel and composite specimens	N/A			N/A	The constitutive parameters of materials measured in isolation show an increase of loss with frequency in all cases.
TECH_NOTE_OFCOM, [19]	1 GHz to 10 GHz	Research			Concrete, brick, plasterboard, wood, glass, ceiling board, chipboard, miscellaneous board and stone material, ground	N/A			N/A	Permittivity and conductivity of the tested materials exhibit all variations with frequency which lead to an increase of the transmission loss when these materials are used in walls.

Virginia Tech Report, [32]	1 GHz to 15 GHz	Measured			Drywall, wall board, structure wood, glass sheet, bricks, concrete blocks, reinforced concrete, cloth office partition, wooden door and styrofoam slab	N/A			N/A	Dielectric constant changes slowly with frequency (some decrease is noticed); attenuation constant is drastically increased with frequency
Wilson, [33]	2.4 GHz to 5 GHz	Measured			Twenty homogeneous and composite materials, including red brick, glass, stucco, cinder block, dry wall, fiber glass, ceiling tile, plexiglas, carpet, linoleum, fir, etc.	N/A			N/A	The authors conclude that there is a frequency dependency on the reflected energy of some of the materials tested
Martijn, [34]	1800	Measured	1	Office block	Concrete	Everywhere	13	2	N/A	The BPL varies significantly according to the building architecture even for same frequency and same materials
	1800	Measured	1	Office block	Concrete	Everywhere	5	4	N/A	
	1800	Measured	1	Office block	Concrete	Everywhere	4	7	N/A	
	1800	Measured	1	Office block	Brick	Everywhere	12	4	N/A	
Stavrou, [3]	400 MHz to 10 GHz	Research				N/A			N/A	A compilation of results is presented on BPL with frequency, as well as explanations of the possible causes of these changes are given.
BellCanada, [35]	700	Research		Residential	Not given	N/A	4.6	Not given	7.05	An increase in BPL with frequency is

	2500	Research		Residential	Not given	N/A	8.5	Not given	7.05	reported for residential buildings; whereas a decrease of BPL with frequency is taken for industrial and commercial buildings
	700	Research		Industrial / commercial	Not given	N/A	14.5	Not given	-7.77	
	2500	Research		Industrial / commercial	Not given	N/A	10.2	Not given	-7.77	
Dalke, [36]	100 to 6000 MHz	Measured			Reinforced concrete	N/A			N/A	Strong dependency of transmission and reflection coefficients with frequency.
Gibson, [37]	2000	Measured			concrete	Shallow	10	Not given	27	In all cases, an increase of BPL with frequency is noticeable. The measurements were conducted not in buildings, but with isolated walls.
	2250	Measured					11.4	Not given	27	
	2500	Measured					12	Not given	27	
	2750	Measured					13.8	Not given	27	
	3000	Measured					13	Not given	27	
	3250	Measured					12.7	Not given	27	
	3500	Measured					15	Not given	27	
	3750	Measured					16.5	Not given	27	
	4000	Measured					16	Not given	27	
	4250	Measured					15.8	Not given	27	
	4500	Measured					16.8	Not given	27	
	4750	Measured					18	Not given	27	
	5000	Measured					20	Not given	27	
	5250	Measured					21	Not given	27	
	5500	Measured					22	Not given	27	
	5750	Measured					22.7	Not given	27	
	6000	Measured					23.5	Not given	27	
	2000	Measured			wood door	Shallow	2	Not given	9.4	
	2250	Measured					4	Not given	9.4	
	2500	Measured					5	Not given	9.4	
	2750	Measured					3	Not given	9.4	
	3000	Measured					3.6	Not given	9.4	
	3250	Measured					4.7	Not given	9.4	
	3500	Measured					6.4	Not given	9.4	
	3750	Measured					4	Not given	9.4	
	4000	Measured					5	Not given	9.4	
	4250	Measured					5.7	Not given	9.4	
	4500	Measured					6.3	Not given	9.4	

	4750	Measured					6.4	Not given	9.4	
	5000	Measured					7.4	Not given	9.4	
	5250	Measured					6.1	Not given	9.4	
	5500	Measured					7	Not given	9.4	
	5750	Measured					7	Not given	9.4	
	6000	Measured					7.1	Not given	9.4	
Hoppe, [38]	230	Measured	4	University campus buildings	Not specified	Everywhere	3.4	13.3	3.52	A slight frequency dependency is acknowledged by the authors. Transmitters were placed at various heights.
	1500	Measured					10.9	7.1	3.52	
	230	Measured					10.4	7.6	3.52	
	1500	Measured					9.7	8.7	3.52	
	230	Measured					7.5	6	3.52	
	1500	Measured					9.3	4	3.52	

List of Acronyms

2G	Second generation systems e.g. GSM, IS-95
3G	Third generation mobile systems, e.g. UMTS
4G	Fourth generation mobile systems e.g. LTE, WiMax
BPL	Building propagation loss
GSM	Global system for mobile communication
ITU-R	International Telecommunications Union – Radiocommunications sector
LOS	Line of sight
LTE	Long term evolution of mobile systems
MNO	Mobile network operator
NLOS	Non line of sight
PCS	Personal Communications Service
RSCP	Received Signal Code Power
UMTS	Universal mobile terrestrial system

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