Building Materials and Propagation

Final Report

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1 EXECUTIVE SUMMARY

1.1 Motivation & background

While building entry loss is an increasingly important parameter in link planning, it is poorly-characterised, partly due to the wide variability within and between buildings. Data relating to domestic buildings is particularly poorly represented.

Ofcom have expressed concern that the increased use of energy-efficient construction practices may be causing building entry loss to increase, and this study was commissioned to address this question.

1.2 Review of building materials & practices

There is a large proportion of older buildings in UK stock, with about 86% of current housing stock built before 1997. These properties tend to be upgraded gradually mainly in response to government initiatives, with the replacement of products such as windows or during major refurbishments, conversions or extensions. While there are general regional differences in construction method, London is something of an exception with higher levels of solid walls and single-glazed windows. New construction over the next decade is likely to represent less than 1% of total stock per year. A particular driver for improving the performance of houses has been the reduction in energy use. This has resulted in Government initiatives (e.g. Green Deal) and changes to the Building Regulations (Approved Document L) have been aimed at improving the thermal performance of houses.

Although not specifically mandated by any regulations, some metallic coated materials have been specifically designed to improve the thermal performance of houses and help meet building regulations. However, their use can also affect the transmission of wireless signals into and within houses. Foil-backed plasterboard gives good thermal performance, acts as a vapour resistant layer and also has minimal impact on the room dimensions. Insulation boards with an aluminium coating on both faces are used in cavity walls and in roofs. Low emissivity (Low E) glazing improves the thermal performance of double-glazed windows by adding a thin metallic or metallic oxide layer to one of the glass panes.

Until recently, there has been a gradual increase in the use of these building products. However, more recently, there appears to be a significant increase in the use of foil-coated products and also significant innovation in an array of new metallic products. For example, this includes “multi-foil” which may typically consist of more than ten layers of aluminium foil and insulation in a product which is highly flexible and which additionally may have improved fire properties. It is now common to see this product stapled to roof eaves and laid on loft floors.
In the future, construction practices and materials may change, particularly in response to more demanding energy efficiency requirements in light of the move to ‘zero carbon’. Beyond 2016 we are likely to see thermal performance for walls tighten further for new dwellings which could further drive the use of foil-backed products.

There is little awareness in the construction industry and potential effects on wireless coverage and the potential choices that may need to be met. Equally, there are no innovative products specifically aimed at solving this potential problem. Awareness needs to be raised in the construction industry about this issue and a debate started about the implications for the ‘Connected Home’/’Smart Home’ agendas

1.3 Review of electrical properties of materials and previous measurements of building entry loss

A comprehensive review has been made of empirical data on the electrical properties of common building materials; it is noted that most measurements are for homogenous material samples rather than, e.g. cavity walls.

A review of the modelling applicable to metalised glass has led to the identification of some errors in existing models.

Measurements of ‘building entry loss’ show a very large spread, but this is partly due to the collation of data that is not strictly comparable. One complicating issue is that a number of different definitions of ‘building loss’ are in use. The characterisation of signal variability into and within buildings is also unsatisfactory in many cases, with little agreement on the definition of terms.

1.4 Measurement campaign

A large body of measured data already exists and the present study can add only a small amount to this. The focus has therefore been 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 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, 217, 698, 2410 and 5760 MHz; in the trials, a transmitter\(^1\) 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 30-50m from the building. Each room in a building was characterised in terms of the median

\(^1\) The transmitter was the portable unit rather than the receiver and logging PC, as it was significantly smaller and lighter. As reciprocity applies the arrangement is immaterial
signal level, and this was related to the field immediately outside the building at the same height to determine the 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 1-1: Overall summary building entry loss results

The relatively high losses seen at 88 MHz appear to be an anomalous feature of House 50.2. No explanation has yet been found for this.

Data has also been gathered on signal variability, which is significantly higher inside buildings due almost entirely to multipath effects. It is not clear that any adequate model yet exists to characterise this variability.

The measurements show increasing levels of building entry loss as modern insulating materials are added to an uninsulated house (see Figure 1-2).
Figure 1-2: 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 5–10dB 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 5dB 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.
2 INTRODUCTION

This report describes work commissioned by Ofcom to examine the impact of building materials on the propagation of radio waves. This work has covered a relatively wide frequency range (100 MHz to 6 GHz) and has focused on the losses experienced by radio signals entering or leaving buildings, and on the impact of different building materials on these losses.

The study was conducted in two phases. The first phase consisted of a review of existing information on materials used in the built environment in the UK, on the electrical properties of materials and on the impact of buildings on radio signals. These reviews are given in Sections 3-5.

The second phase of the work consisted of a measurement campaign involving buildings located at the Watford campus of BRE Global Ltd, with results reported in Sections 6 and 7 of this document.

2.1 Background

Consumers increasingly expect wireless devices of all kinds to provide seamless coverage, both outdoors and indoors. To meet this expectation places great demands on the infrastructure of any radio network, implying the need for higher powers, more dense networks or both. In all cases, interference within and between networks will tend to increase. These problems can be minimised by exploiting the intelligence that is increasingly available to radio systems, through approaches such as MIMO, beamforming, or ‘data-offload’ to other networks (e.g. from cellular to Wi-Fi).

Perhaps the greatest problem associated with providing in-building coverage is not so much the increase in the average path loss, but the great increase in the variability of path loss that must be allowed for. One of the reasons cited for the substantial interest in the spectrum at 800 MHz recently released for mobile use is that the spatial variability of the indoor signal is lower than it is at higher frequencies. Recent measurements by Aegis and Signal Science in the Ofcom ‘in home’ study [3.18] demonstrated the superior coverage obtained at lower frequencies.

In other cases, the transition to digital technologies has changed the perceived degradation of services indoors; in planning for a possible ‘digital switchover’ of broadcast radio, the fact that a marginal signal will result in the muting of the receiver, rather than an increased audio noise level has led to a reassessment of indoor coverage criteria.

Spectrum planners are interested not only in the degree of penetration of radio services into the home, but also in understanding the leakage from indoor devices that may cause interference to neighbouring systems. The primary example is probably that of Wi-Fi systems operating at 2.4 GHz, where congestion is an increasing problem in many areas, but the topic has also been of strategic interest lately in assessing options for ‘smart metering’ of domestic electricity and gas supplies.
There has been much anecdotal suggestion that changes in building practices, in particular with regard to thermal insulation, are having a detrimental impact on indoor radio coverage. There appears to be little direct evidence to support these assertions, however. One recent Report for Ofcom [3.19] cites measurements made in Ireland to suggest that “changes in construction methods and materials, and in particular the effect of low-emissivity glass with metallic oxide coatings” imply that “the margin to allow for building penetration losses might need to be increased”. An additional margin of 9dB at 2.1 GHz is mentioned.

The paper [3.20] describing the measurements is intended more for marketing than academic purposes, but does not suggest that the 9dB figure is linked to any change in construction practices, suggesting rather, that existing planning methods fail to account for indoor signal variability adequately.

The work undertaken has provided a systematic review of existing information on the topic, and has added a limited, but well-characterised, set of empirical data to illustrate the impact on building entry loss has of different materials.
3 CHARACTERISATION OF UK BUILDINGS AND MATERIALS

3.1 Scope

The focus of this section is on residential buildings in the UK, their construction form, the original materials used and materials that have subsequently been installed following refurbishment. Non-residential buildings – primarily offices – are considered in a previous report for Ofcom².

There are currently some 23 million houses and flats in the UK. The construction rate for new dwellings has been about 110,000 over the last 2-3 years, although the first half of 2013-14 has seen a significant upturn:

![Figure 3-1: Trends in housing starts and completions, England, 12 month rolling totals (ONS)](image)

Nevertheless, when considering the demolition rate is only some 10,000-20,000 units per year, it is clear that a key focus of any study into the attenuation of radio waves needs to consider the performance of the existing housing stock, its original construction form and any improvements it has undergone. Specifically, 70% of the stock in 2050 has already been built:-

The housing stock continues to improve at a pace and we are seeing the introduction of many new and innovative construction materials which are designed to improve the energy performance of dwellings which are particularly relevant to this study. That is not to say that new-build is to be ignored, as many of these products are employed in this sector too.

### 3.2 Existing stock

#### 3.2.1 Improvement programmes

The existing stock has been subject to many improvement programmes and grant based initiatives since the 1970s. This has accelerated in the last ten years or so with the introduction of statutory obligations on the energy supply companies and, more recently, the generators to achieve energy efficiency improvements amongst their domestic customer base in order to achieve energy and carbon reduction targets.

The associated programmes were Energy Efficiency Commitment (EEC1 and EEC2), Carbon Emissions Reduction Target (CERT) and Community Energy Saving Programme (CESP). The main measures installed under these programmes have been cavity wall insulation (CWI), loft insulation and low-energy lighting as well as replacement condensing boilers. These measures are the so-called ‘low hanging fruit’ as the energy companies have focussed on the most cost-effective measures to achieve their targets. More expensive measures such as solid wall insulation (SWI) and floor insulation were
installed under these programmes – there were associated carbon ‘uplifts’ to encourage them - but they still were not taken up that widely.

These programmes have now been replaced by Green Deal and the Energy Company Obligation (ECO). Green Deal is a market framework which enables private firms in GB to offer consumers energy efficiency improvements to their homes, community spaces or businesses at no upfront cost with repayments recouped through a charge made in instalments on their energy bill. Operating across all types of property tenure, the Green Deal works alongside the ECO which provides additional support for packages of energy efficiency measures such as SWI. The ECO also provides insulation and heating packages to low income and vulnerable households and insulation measures to low income communities.

In parallel with this, owner occupiers (who make up about 70% of the total stock) have sought to improve their properties through window replacements (mostly driven by aesthetics and the need to replace old and worn-out windows), loft conversions, extensions, installing central heating systems etc.

In the social sector there has been the Decent Homes programme which has seen the installation of new bathrooms and kitchens as well as the installation of CWI, loft insulation, double glazing and efficient heating systems to ensure all social housing achieves the decent homes standard.

3.2.2 Building Regulations

The benchmark for all refurbishment work undertaken under these programmes is determined by the Building Regulations, the key document in this case being Approved Document (AD) L for England & Wales with equivalent technical guidance in Scotland and N Ireland. The regulations require that whenever ‘building work’ is carried out, reasonable provision should be made to improve the efficiency of the thermal envelope (walls, floors, roof, windows and doors), heating and other fixed services. Improvements are required when undertaking the following types of work:

(i) Extensions to existing dwellings
(ii) Change of use (e.g. a barn conversion)
(iii) Alterations to dwellings (e.g. replacement of an external wall)
(iv) The provision, replacement or renovation of a thermal element - a thermal element is a wall (excluding windows and doors), floor or roof that separates the heated space from the outside or from an unheated space, such as an integral garage
(v) The provision or replacement of controlled fittings (windows, external doors etc.)
(vi) The provision, replacement or extension of a controlled service (or part) - controlled services include heating and hot water systems, lighting, mechanical ventilation and cooling.

Prior to 2002, the only requirements on existing buildings were the first three areas but with the introduction of the 2002 edition of Part L the scope was extended such that there
is now a separate AD for existing dwellings: Part L1B. There have been further revisions in 2006, 2010 and 2014 which have involved tightening the technical requirements and clarifying the guidance.

The performance requirements are framed in terms of maximum ‘U-values’ (heat transfer coefficients) for walls, floors and roofs as well as replacement windows and doors. Replacement boilers need to have a minimum seasonal efficiency figure and a minimum controls system needs to be provided when whole heating systems are installed. The requirements are designed to be reasonable and can be relaxed if they are shown to be not cost-effective or technically not possible. Accordingly, the standards required under the various improvement programmes have had to evolve with them.

Compliance with the Building Regulations for existing dwellings is generally achieved through local authority building control departments. However, given the vast scale of work undertaken each year, compliance for individual measures is often accomplished through competent persons’ schemes where installers self-certify compliance with the regulations. This is particular the case for window replacements (through the Fensa scheme), installation of heating systems (Gas Safe for mains gas, Oftec for oil and LPG and Hetas for solid fuel) and CWI (Cavity Wall Insulation Self Certification scheme, CWISC). There are also technical approvals of insulation products through, for example, BBA (British Board of Agrément) certificates and, more recently, saw the introduction of SWIGA (Solid Wall Insulation Guarantee Association) that provides a 25-year guarantee for SWI installations.

As part of their statutory obligation under the previous energy efficiency programmes and now under ECO, the energy companies are required to audit a sample of their installations to ensure that they meet the requirements of Building Regulations and other technical standards. This can be done in-house by the company or they can commission a third party. The results have to be reported to Ofgem, who administer the ECO, and the companies need to demonstrate adequate levels of compliance and that action is being taken where there are problems. In addition, Ofgem will commission independent bodies to undertake inspections of measures.

Installations under Green Deal are covered by the same requirements and this is administered by the Oversight and Registration Body (ORB). The GD ORB’s role includes:

- maintaining a register of all authorised Green Deal Providers, Certification Bodies, Advisors and Installers; maintaining the Green Deal Code of Practice
- controlling the use of the Quality Mark
- ongoing monitoring of Green Deal Participants against the Code of Practice
- producing an annual Green Deal report
- gathering evidence of non-compliance and referring participants to the Ombudsman or the Secretary of State where appropriate and imposing sanctions when directed.
The level of compliance with Building Regulations, i.e. the degree to which they are met, is therefore likely to be high, particularly with regard to health and safety. Nevertheless, there is evidence to suggest that despite the considerable body of technical assessment and enforcement supporting installations, there can be a gap in energy performance between design and what is seen is reality. Part of this can be attributable to 'thermal comfort take-back', where the introduction of new heating systems tend to result in householders raising the thermal comfort of the home (i.e. having warmer houses). Therefore, some of the potential reductions in energy use and expenditure are forfeited by the home owner in order to have warmer homes. The balance is therefore attributable to incorrect specification of product, poor installation and commissioning etc. As a consequence, DECC and Ofgem have introduced so-called 'in-use factors' that reduce the savings attributable to each energy efficiency measure when installed in the context of Green Deal and ECO, but these are reviewed in light of evidence from field trials etc.

### 3.2.3 Construction form and materials

#### 3.2.3.1 Introduction

In light of the improvement work that the existing stock has been subject to over the years this has resulted in a significant growth in energy efficiency products some of which may have an impact on the propagation of radiowaves. Key materials here that have been identified – see Section 4 for further detail – include double-glazed windows and foil-backed insulation. In addition, the original form of construction can have a significant effect possibly because of inhomogeneity (e.g. cavity walls) and a high metallic content – again see Section 4.

The specific types of material and forms of construction used are discussed below.

#### 3.2.3.2 Building Regulations

There are 14 Approved Documents that support the fourteen technical "Parts" of the Building Regulations (England & Wales) together with Regulation 7. These are:

- Approved Document A (Structural safety)
- Approved Document B (Fire safety)
- Approved Document C (Resistance to contaminants and moisture)
- Approved Document D (Toxic Substances)
- Approved Document E (Resistance to sound)
- Approved Document F (Ventilation)
- Approved Document G (Sanitation, Hot Water Safety and Water Efficiency)
- Approved Document H (Drainage and waste disposal)
- Approved Document J (Heat producing appliances)
- Approved Document K (Protection from falling)
- Approved Document L (Conservation of fuel and power)
• Approved Document M (Access to and Use of Buildings)
• Approved Document N (Glazing safety) From 6 April 2013 - Only relevant to Wales
• Approved Document P (Electrical Safety)
• Approved Document 7 (Workmanship and Materials)

As noted above, Approved Document (AD) L is split into four documents to cover new-build and existing, domestic and non-domestic buildings. Part L is also supported by associated technical compliance guides.

Given the focus on radio propagation through buildings a review of the salient features of construction and construction products since 1985 has been undertaken. The focus is on the ADs for England & Wales but equivalent guidance is provided in Scotland and Northern Ireland.

New dwellings

Since 1985:

• Part A – All dwellings require thin wire steel wall ties, lateral restraint straps, gang-nailed plates on roof trusses, joist hangers and metal lintels/beams

• Part C – All dwellings require lead flashings in key locations, e.g. around dormers, vent pipes, gulleys, roof valleys, chimneys, some bay windows, abutment of single storey to two storey, staggered/stepped party walls.

• Part J – Heating system, boiler, radiators, hot/cold pipework, gas pipework in all non-electrically heated dwellings. Flats over 3-storeys are generally electrically heated but will still have metal pipework for hot/cold water.

• Part K – External metal staircases to 2 and 3-storey flats, although proportion where installed would be low. Taller flats would have common internal stairs, which might be metal but more likely concrete

• Part L – Occasional use of foil backed plasterboard to ceilings in wet rooms with roof voids over (bathrooms etc.), occasional use of foil backed plasterboard on battens as dry lining to the inside of external walls.

1990 edition of Part L:

• For the first time, the use of double glazing with a low-e coating is included. Here it meant that the glazing area of the dwelling could be trebled if double glazing with low-e was used instead of single glazing. This option might have been chosen for larger bespoke new detached dwellings, but most likely single glazing was still used in the main. Probably only 5% of dwellings would have low-e glazing.

• Partial fill cavity wall insulation used in high driving rain index (Index 4) locations and occasionally this would be foil-backed. The driving rain index map shows that Index 4 locations cover about a quarter of the UK, mostly in the West but these are generally outside of major population areas so this would only address 10% of new dwellings at most.
Occasional use of foil-backed plasterboard on the inside of external walls in timber-framed dwellings as lower wall U-value required allowing the use of thinner wall insulation (i.e. residual air cavity between insulation and plasterboard). Although popular in Scotland, timber frame was not widely used in England so across the UK it made up only about 5% of new dwelling construction at this time. Nevertheless, perhaps up to half of such dwellings would have used foil-backed plasterboard.

1995 edition of Part L:

- Following tightening of window and door U-value requirements, double glazing becomes the norm but this would predominately (i.e. 90%) be 6mm airspace without a low-e coating. There would be occasional use of low-e coatings to trade-off a relaxation of fabric U-values as part of the overall design. Glazing incorporates a metal spacer bar between panes and this would be present in all window frame types.

- In subsequent years there was a move to wider spacing for windows, at least 12mm air gap but more usually 16 or 20mm. Framing was predominately PVCu (70%) with the majority of the balance being timber.

- Partial fill cavity wall insulation used in high driving rain index locations, and foil-backed insulation becomes the norm

2002 edition of Part L:

- The key change here of relevance to radio wave propagation was that the glass in double glazed windows with low-e coating became the norm

The graph below shows the new-build construction rate for dwellings in the UK since 1978 to 2012 and, where data is readily available, it also contains the breakdown by flats and dwellings and the growth of timber frame construction since 1996. This graph shows an average of the number of completions and starts, which is a single value used by the industry to gauge the state of the market. Individual start and completion data is shown in Figure 3-1, although slightly different time windows are used making direct comparison slightly difficult.
Figure 3-3: Average of completions and starts for UK dwellings (Source: ONS & NHBC)

Using this data we can estimate that:

- Since double glazing became the norm in 1995 some 3.3 million dwellings have been constructed and nearly 2m of these have had glass with a low-e coating.
- Since 1995 over 200,000 timber-framed dwellings have used foil-backed plasterboard
- Since 1990 over 350,000 new dwellings have used foil-backed plasterboard in partial filled cavities.

**Existing dwellings**

Metal is present in existing dwellings, for example:

- Early cavity wall construction included heavy duty iron wall ties
- Wide use of metal rainwater goods and above ground drainage stacks etc.
- Metal weights in sliding sash type windows
- Levels of pipework increase from single lead water supply through to full heating/hot water systems and gas pipes
- Copper or lead flashings

As noted above, prior to 2002 Part L only applied to conversions and extensions. Here, extensions to existing dwellings would more or less be same as new build dwellings. Conversions of roof spaces and garages to habitable spaces would also be similar to new build, but there would be limited use (probably <5% of projects) of multi-foil insulation between 1995 to 2006.
2002 edition of Part L:

- Replacement glazing included for first time and, in line with the new-build requirement, double glazing with low-e coating was required with either 12mm or 16mm airspace. Glazing incorporates a metal spacer bar between panes.

2006 edition of Part L:

- Renovation of thermal elements (i.e. walls, roofs etc.) requires inclusion of insulation for the first time (over minimum trigger proportion of element area). There was potential use of foil-backed insulated laminate plasterboard on battens when internally insulating solid walls, possibly a third of such installations.

3.2.3.3 Growth of energy efficiency measures

In light of the energy efficiency activity and programmes described above we can estimate the impact in terms of the number of measures that have been installed, in particular those that could have an impact on radio wave propagation.

Data sources include the UK Housing Energy Fact Files which are published by DECC [1-2]. The graphs below show the growth of loft insulation, CWI and double glazing respectively:

![Figure 3-4: Growth of loft insulation ownership [1-2]](image-url)
Figure 3-5: Growth of cavity wall insulation ownership [1-2]

Figure 3-6: Growth of double glazing ownership, 1983-2007 [1-2]
On the basis of this data, for example, and, allowing for the new-build activity discussed above, would suggest that some 3.0 million existing householders have acquired low-e double glazed windows since 2002 and that in over 90% of cases more than 80% of the dwelling’s windows are of this type. The large increase in the number of properties having more than 80% of their windows double-glazed from 2002 is likely to be due to a change in the data collection method, from the previous GFK data set to the EHS data set, as noted in [1-2]. The changes in Approved Document Part L in 2002 to include the requirement for replacement windows to be double glazed would not have had this effect.

Further discussion of window frame type is given in the next section.

Ofgem has also published tables summarising the numbers of measures that have been installed under the various programmes that they manage:

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**Figure 3-7: Growth of double glazing ownership, 2008-2011 [1-2]**

On the basis of this data, for example, and, allowing for the new-build activity discussed above, would suggest that some 3.0 million existing householders have acquired low-e double glazed windows since 2002 and that in over 90% of cases more than 80% of the dwelling’s windows are of this type. The large increase in the number of properties having more than 80% of their windows double-glazed from 2002 is likely to be due to a change in the data collection method, from the previous GFK data set to the EHS data set, as noted in [1-2]. The changes in Approved Document Part L in 2002 to include the requirement for replacement windows to be double glazed would not have had this effect.

Further discussion of window frame type is given in the next section.

Ofgem has also published tables summarising the numbers of measures that have been installed under the various programmes that they manage:
### Table 3.1: Ofgem measures under each energy saving scheme.

<table>
<thead>
<tr>
<th>Measure</th>
<th>EEC 1 (2002-05) &amp; EEC 2 (2005-08)</th>
<th>CERT (2008-12)</th>
<th>CESP (2009-12)</th>
<th>Total number of measures (installations or m² for radiator panels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity wall insulation</td>
<td>2,127,899</td>
<td>2,568,870</td>
<td>3,000</td>
<td>4,699,769</td>
</tr>
<tr>
<td>Solid wall insulation</td>
<td>59,008</td>
<td>58,916</td>
<td>80,257</td>
<td>198,181</td>
</tr>
<tr>
<td>Loft insulation (top up)</td>
<td>1,470,778</td>
<td>3,897,324</td>
<td>23,503</td>
<td>5,933,375</td>
</tr>
<tr>
<td>Loft insulation (virgin)</td>
<td>541,770</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIY loft insulation</td>
<td>1,004,308</td>
<td>2,507,800</td>
<td></td>
<td>3,512,108</td>
</tr>
<tr>
<td>Boilers</td>
<td>2,361,803</td>
<td></td>
<td></td>
<td>42,898</td>
</tr>
<tr>
<td>Heating controls + boilers</td>
<td>196,068</td>
<td>31,986</td>
<td>60,016</td>
<td>2,632,755</td>
</tr>
<tr>
<td>Radiator panels (m²)</td>
<td>96,747</td>
<td>259,851</td>
<td></td>
<td>356,598</td>
</tr>
</tbody>
</table>

The figures in the table represent the number of installations of each particular measure under each of the government schemes over the periods of time defined, except for radiator panels which is per m² of panel installed. It should be noted that there are likely to have been other installations outside of these schemes which were not formally recorded. With regards to modifications of the building external walls, about 96% of installations were for cavity wall insulation where the cavity in the wall is filled but no foil-back plasterboard is used on the internal wall. The amount of solid wall insulation is relatively low at about 4% of the total external wall measures. In addition, the vast majority (>90%) of these solid wall measures is likely to be insulation on the external of the wall. Therefore, the use of foil-backed plasterboard for improving the energy performance of external walls appears to be very small, only of the order of a few thousand installations. However, these figures are subject to a great deal of uncertainty given that a lot of activity may not be recorded.

#### 3.2.3.4 English Housing Survey

In terms of understanding the original construction form and the current levels of insulation there is the English Housing Survey (EHS). This is a continuous national survey commissioned by the Department for Communities and Local Government (DCLG). It collects information about people’s housing circumstances and the condition and energy efficiency of housing in England and supports DCLG’s housing policies. It consists of:

- an interview survey which is conducted with all householders in the sample (around 13,300 households per year), and,
- a **physical survey** which involves a physical inspection by qualified surveyors of a subsample of around 6,200 properties per year.

The most recent data is for 2011-12.

The graphs below show the occurrence of different construction forms that may have an impact on radiowave propagation.

### 3.2.3.4.1 Wall type

![Graph showing frequency of distribution of wall types across English regions](image)

**Figure 3-8: Frequency of distribution of wall types across English regions**

Perhaps unsurprisingly the graph shows the dominance of cavity walls across nearly all regions of England, the exception being London where solid walls contribute half of the overall figure. As indicated by the insulation figures above around two-thirds of potential cavities have now been filled. Solid wall dwellings number 5.4 million of all English dwellings (i.e. about 24%) but less than 200,000 of them (<4% are insulated). Dwellings with metal sheet only contribute a small amount to the overall total but are potentially of the most interest to this study and so these are discussed further in the next section.
3.2.3.4.2 Window glass and framing

Figure 3-9: Frequency of distribution of window glass and frame types across English regions

This graph supports the data presented earlier as it shows the dominance of double glazed units across the country. The distribution is reasonably consistent across most of the regions with London again being the exception with a disproportionately high level of single glazing, in particular with sash windows. London is also the exception with regard to framing as it high levels of metal framed windows, although overall the proportion of such framing is small, only 5%. The dominant form of framing is PVCu, making up just over three-quarters of all windows. Further analysis indicates that in three-quarters of cases of PVCu doors and also found with PVCu windows – much of the remainder have wooden doors.

3.2.3.4.3 Wall and window types

It is instructive to look at the occurrence of walls and windows in combination as in the graph below:
Figure 3-10: Frequency of distribution of window and wall types across England

The graph again shows the high preponderance of masonry cavity construction but we can also see that 95% of such dwellings have double glazed windows. The next highest wall type is solid wall (either 9" thick or wider) and again double glazing dominates but the proportion is lower: 75%. Solid wall dwellings have a higher proportion of single glazed windows most of which are wood framed (equally split between casement and sash).

3.2.3.4.4 Roof type and material

The final analysis from the EHS is of roof type and material and this is shown in the graph below:
Figure 3-11: Frequency of distribution of roof types and materials across England

As might be expected pitched roofs dominate: 92% of roofs are of this form. The majority (79%) of these roof constructions have either concrete or clay tiles with the balance either a natural or man-made slate. It is difficult to quantify the number of roofs with a metal form but they are probably less than 1%.

3.2.3.5 Non-traditional dwellings

Given the particular interest in those dwellings with the potential to reduce radiowave propagation it is instructive to identify those forms that may have a significant impact. One such example is metal-framed construction which cannot easily be identified within the EHS but they can be through a database of non-traditional dwellings. Nearly ½ million such dwellings were built in the UK period 1918-1975. Such dwellings are grouped into four forms of construction: metal frame (M), precast concrete (P), in-situ concrete (S) and timber framed (T).

An analysis of the database indicates that about 300,000 metal framed dwellings were constructed with a wide range of construction forms: steel frame, iron frame and panels, steel frame and aluminium panels, steel frame and foil-backed plasterboard etc. The graph below shows the 77 metal framed types identified together with the number constructed and the distribution across the UK:

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Figure 3-12: Distribution of metal-framed building types

It is immediately clear that the situation is dominated by only about ten types which make up about 90% of the total number built. There is a long tail to the distribution which shows that for many types only a handful were actually built. Some types are far more prevalent across the UK and can be found in over 150 different areas.

However, it should be borne in mind that this is the total number constructed and not what is currently standing. Many of these dwellings were constructed quickly and have gone beyond their expected lifetime. Some have been designated defective and require remedial work. As a consequence a disproportionate number have been demolished over the years in comparison to more traditional dwellings. This is the case for the most ubiquitous dwelling (M002) which has been subject to a demolition programme.

Data from the most recent EHS indicates that there are still some 200,000 metal framed dwellings and these will be dominated by a handful of key types, specifically the BISF Type A1 (M017), Trusteel Mk II (M097) and Trusteel 3M (M098) which are all widely spread throughout the UK. Details on their construction form is given in Annex C.

3.3 Future dwellings

Past and current Building Regulation requirements and how these have given rise to materials and construction forms that could impact on radio wave propagation have been discussed above. Moving forward, we can suggest how construction practices and materials may change in the near future, particularly in response to more demanding energy efficiency requirements in light of the move to ‘zero carbon’.

In the next few years there is unlikely to be a need for a step change and that an evolution of current practice will meet requirements. The current (2013) version of Part L effectively only calls for a 6% carbon reduction for new dwellings relative to the previous
(2010) edition. Foil faced partial fill insulation will be used in high rain index areas, and full fill cavity wall construction will still use mineral wool. Glazing will probably be high performance double glazing (U<=1.2 W/m².K) as whilst triple glazed units have better U-values they have low g-values (solar transmittance) and a higher cost.

Metal spacers in glazing units are being replaced by plastic composites given the improved thermal performance. This also means that air-filled double glazed units achieve the Band C BFRC (British Fenestration Rating Council) rating which is the minimum performance requirement for replacement windows. Triple glazed units may be too bulky and heavy to be installed into some existing dwellings, and by not setting too high a performance requirement allows SME fabricators to continue providing windows to the refurbishment market without significant re-tooling.

Moving forward to 2016 and beyond we are likely to see wall U-values for new dwellings down to 0.20 and lower, so walls would need to become thicker with cavities having sufficient width to accommodate 150mm (or more) full fill mineral wool insulation. The alternative is to use foil backed insulation. Triple glazed units may well become more prevalent.

A good description of likely construction forms and materials for new dwellings is given by the AIMC4 project⁴. This Technology Strategy Board (TSB) funded project had five partners - 3 volume house builders (Stewart Milne Group, Crest Nicholson and Barratt Developments), an Aircrete concrete supplier (H+H UK) and BRE – with the aim to pioneer the volume production of Code 4 houses by adopting a ‘fabric first’ approach rather than relying on renewable technologies.

In total 17 AIMC4 dwellings were constructed using various forms of construction that are likely to be adopted in the coming years. The systems used were: thin-joint mortar masonry, structural insulated panel (SIPs) system, closed-panel timber frame and open-panel timber-frame, all in conjunction with triple or high performance double glazing.

Polyisocyanurate (PIR) foam boards were used to insulate the masonry cavity walls. Two types of PIR product were used. The first was a partial-fill cavity wall insulation solution with wider-than-conventional cavities to accommodate a greater thickness of insulation whilst maintaining a residual cavity. The second product was a full-fill PIR cavity insulation board with a moulded (not expanded) polystyrene face. In both cases the boards had foil backing.

The SIPs system is based on composite panels comprising 15 mm OSB3 (oriented strand board) outer skins that are adhesively bonded to a polyurethane (PU) foam core. These are manufactured off-site thereby improving quality, and with the insulation integrated into the structural element this results in potentially thinner constructions. The SIP system was then given a brick outer leaf.

The open-panel timber-frame system used rigid PU insulation and a dedicated service zone behind the plasterboard in order to achieve the U-values required. The closed

⁴ The project website can be found at: http://www.aimc4.com/index.jsp
panel system comprises wall panels and floor cassettes based on engineered timber C-stud structural elements enclosed on both sides with OSB. The panels are fully filled with bonded high-performance EPS (expanded polystyrene) insulation beads containing graphite (this reduces the thermal conductivity of conventional EPS). Walls are finished internally with plasterboard on battens to provide a service void for electrical heating and plumbing services.

Further details on all the constructions can be found in a BRE Information Paper\(^5\).

One final point to note about future direction of regulations is the drive to narrow the so-called performance gap, i.e. the gap between design and the energy performance in practice. This was referred to above in the context of refurbishment but the phenomenon is also prevalent in new dwellings. The government is working closely with the house building industry to address this issue and there is the aim that by 2019 90% of new dwellings will meet or exceed their design energy performance. Further details on this initiative can be found on the Zero Carbon Hub website\(^6\).

### 3.4 Summary & Conclusions

Building materials and methods have changed over the last few decades to meet the requirements for the improved performance of houses. Two particular drivers are the building regulations and government incentives.

With regards to building regulations, one key document is Approved Document L (“Conservation of fuel and power”) for England & Wales with equivalent technical guidance in Scotland and N Ireland. This requires that whenever ‘building work’ is carried out, reasonable provision should be made to improve the efficiency of the thermal envelope (walls, floors, roof, windows and doors), heating and other fixed services.

Incentives to achieve energy and carbon reduction targets were introduced in the 1970s but have accelerated in the last ten years or so.

Some metallic materials can help improve the thermal performance of houses but can also affect the transmission of wireless signals into and within houses. Aluminium foil has a very low thermal emissivity and in addition can provide a vapour resistant layer. It is incorporated into foil-backed plasterboard and many modern insulation boards for example. Foil-backed plasterboard gives good thermal performance balanced with having minimal impact on the room dimensions. The insulation boards are used in cavity walls and roofs. Low emissivity (Low E) glazing improves the thermal performance of double-glazed windows by adding a thin metallic or metallic oxide layer to one of the glass panes.

The pace and extent of new products and materials being introduced into houses depends on the balance between new-build and refurbishment and the impact of

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regulations and the performance of the economy and housing market. About 86% of current housing stock was built before 1997. New construction over the next decade is likely to represent less than 1% of total stock per year. To meet improved regulations, refurbishment and extensions are likely to represent the majority of changes to house construction. However, new construction is likely to result in more extensive use of the materials described above.

For new-build, since double glazing became the norm in 1995 some 3.3 million dwellings have been constructed and nearly 2m of these have had glass with a low-e coating. Since 1995 over 200,000 timber-framed dwellings have used foil-backed plasterboard. Since 1990 over 350,000 new dwellings have used foil-backed plasterboard in partial filled cavities.

For existing houses, prior to 2002 conversions and extensions would more or less be built the same as new build dwellings. Conversions of roof spaces and garages to habitable spaces would also be similar to new build, but there would be limited use (probably <5% of projects) of multi-foil insulation between 1995 to 2006. From 2002, replacement glazing was included in AD Part L for first time and, in line with the new-build requirement, double glazing with low-e coating was required. From 2006, AD Part L included insulation for the first time. It is estimated that foil-backed plasterboard has been used in about one-third of improvements involving insulating solid walls, although the figures may be low.

There is no regulatory driver that specifically mandates the use of foil-backed plasterboard or insulation. However, these products have been specifically design to allow regulations to be met in an effective way and are therefore popular.

In the future, construction practices and materials may change, particularly in response to more demanding energy efficiency requirements in light of the move to ‘zero carbon’. Beyond 2016 we are likely to see thermal performance for walls tighten further for new dwellings which could further drive the use of foil-backed products.

There is little awareness in the construction industry regarding the impact on wireless coverage and the potential choices that may need to be met. Equally, there are no innovative products specifically aimed at solving this potential problem. Awareness needs to be raised in the construction industry about this issue and a debate started about the implications for Connected Home/Smart Home agendas which are likely to require the increased use of wireless products to achieve effective energy management, as well as addressing other industries such as communications, entertainment and telehealth for example.
4 ELECTRICAL PROPERTIES OF MATERIALS

This section reviews how individual building materials affect a radiowave impinging on them. In particular we are interested in the loss experienced by the radiowave in passing through the material. The loss depends on the frequency and the angle of incidence of the radiowave as well as on the materials themselves.

A recently approved new Recommendation of the ITU-R (P.2040) [2.1] is very relevant to this discussion. It defines basic quantities related to the electrical properties of building materials and building entry loss, describes the effects of material structure on radiowave propagation, gives a compilation of electrical properties of materials and building loss measurements, together with simple models where appropriate. The compilation of material properties originates in an earlier Ofcom study [2.4].

It is necessary to distinguish between the basic materials, such as brick or glass, and the building materials and structures that incorporate these materials, such as a brick wall or a window. This study covers frequencies from ~100 MHz to 5 GHz, corresponding to wavelengths from 3m to 6cm. When the dimensions of a structure become comparable to the wavelength it may not respond in the same way as a “basic” material. Structures such as cavity walls and double glazing come into this category.

4.1 Effects of building materials on radiowave propagation

Radiowaves impinging on a building will enter the building by various mechanisms. The influence of the electrical properties of building materials on each mechanism is different. Material properties have a dominant effect on the reflection from, and transmission of, radiowaves through building materials and on the absorption of radiowave energy in those materials. These effects give rise to attenuation of the signal, and are discussed first.

Other mechanisms include diffraction from the edges of materials and scatter from rough surfaces. Only a brief discussion of these mechanisms is given since the electrical properties of the building materials are of secondary importance in determining their effects on the radio signal. This does not imply that the mechanisms are unimportant. In particular diffraction can be the dominant propagation mechanism by which radio signals reach a receiver location.

The ability to treat propagation mechanisms such as reflection separately from diffraction and scatter arises from the fact that building elements such as walls, windows and doors are generally quasi-two-dimensional structures with sharply defined edges and faces that are planar and smooth on the scale of a wavelength. Whilst this is only approximately true, and is frequency-dependent, all detailed computational models for propagation into and within buildings make these assumptions.

All normal building materials are non-magnetic and non-ionised. This means that we only need to consider the dielectric properties of building materials. Most building materials behave as lossy dielectrics. Even metals can be characterised in this way, although the RF losses through metal are very high.
4.1.1 Reflection, transmission and absorption

When a radiowave propagating in the atmosphere impinges on a dielectric material such as a wall or window it will be refracted by the material. Part of it will be reflected back and part will be transmitted through the material into the building. The magnitude and phase of the reflected and transmitted components are given by the well-known Fresnel reflection and transmission coefficients. These in turn depend on the dielectric properties of the material, and on the angle of incidence of the radiowave to the material.

From the point-of-view of a receiver inside the building, the wave reflected by the outside wall represents a loss. But there is an additional (generally more significant) loss due to the fact that the building material is lossy. This gives rise to attenuation of the transmitted wave as it propagates through the material due to absorption. Absorption results in ohmic heating. The absolute amount of heating is very small since the energy flux of the radio signal is also very small, but the mechanism can cause serious attenuation to the signal. The attenuation in decibels is simply proportional to the depth of material through which the signal propagates. So while the total attenuation will depend on the angle of incidence of the radiowave to the building (through a secant dependence of material depth on incidence angle), the attenuation rate (dB per metre, say) is an intrinsic characteristic of the material and does not depend on incidence angle.

The calculation and measurement of reflection and absorption losses is made more complicated when, as is usually the case, the building materials are not simple homogeneous substances. Glass, for example, may be considered a homogeneous material since its electrical properties are the same at any two points in the material separated by distances much less than any wavelength of interest. This is not true of most building materials. For example brick, concrete and wood all have some degree of granularity, due either to an intrinsic mix of materials, or to variations in the density or porosity of the material. The issue is whether the scale of these inhomogeneities is much smaller than the wavelength. If it is, then the material may be considered “homogeneous”, with an “effective” dielectric constant that can be used to model the material in the same way as a truly homogeneous material. Even eminently compound materials, such as a brick wall composed of discrete brick and mortar layers, can be dealt with in this way as long as the dimensions of the material variations are small compared with the wavelength of interest. At the frequencies of interest to this study, it is a good approximation to treat such objects as homogeneous.

Another example of inhomogeneity occurs in the case of multi-layered materials. This would include such things as cavity walls, double glazed windows and foil-backed insulation. In general many “modern” building materials are of this sort. In these cases the width of the layers, or the gap between layers may be comparable to the wavelength at the higher frequencies. The effects are illustrated in Figure 4-1 showing the calculated transmission loss for glass due to refractive effects (i.e. loss caused by reflection at the interface).
Figure 4-1: Example transmission loss of compound materials

The glass interface result is virtually independent of frequency, but is not representative of building materials as the thickness of the glass is assumed to be infinite. The concept of Fresnel reflection and transmission coefficients for a single layer can be extended to dielectric materials comprising several layers. The result for a 6mm glass sheet (air-glass-air) shows an oscillatory dependence of loss on frequency, for frequencies above 5 GHz. This is caused by resonances within the glass sheet, although the effect is only ~3dB. When a second sheet of glass is included, separated from the first by a 20mm gap (typical of double glazing), the oscillations become deeper and begin at a lower frequency, ~1 GHz.

These effects are real but are difficult to incorporate in simple propagation models. The reason is that the frequency-dependence is very sensitive to the material and gap dimensions and non-uniformity of these in real building materials is likely to smear out the oscillations. Another reason is that the amplitude and phase of the oscillations also depend on the angle of incidence of the radiowaves on the material. In Figure 4-1 the incident wave was normal to the glass. Figure 4-2 shows the angle dependence at 30 GHz. Again a simple propagation model is unlikely to include the complexity of accounting for the angles of specific building materials.
This oscillatory behaviour of compound materials is an elementary example of a frequency selective surface (FSS). Much work has gone into designing materials for use in buildings that could selectively pass or stop a band of frequencies over a wide range of incidence angle. An example of double glazing incorporating a low emissivity metal film manufactured with an annular slot geometry tailored for a passband between 800 MHz and 2 GHz is given in [2.2].

The oscillatory behaviour in transmission loss shown above is due entirely to refractive effects in the compound materials. Absorption losses, which are not sensitive to the phase of the radio wave, do not show this behaviour. There may be some frequency dependence of absorption losses due to dependence of a material's dielectric properties on frequency, but this dependence is generally slow and smooth. In compound materials such as double glazing, the overall absorption loss is just the sum of the absorption losses of the individual constituent materials.

This study does not include FSS materials, and as far as possible will not consider the oscillatory behaviour of compound materials explicitly as a function of frequency or angle. In common with most measurements of building entry loss this variability will be present in the measurements and will contribute to the standard deviation of the loss. Some consideration of these effects may be required however if new measurements of specific “modern” compound building materials are required.

Reflection of a radio wave from an outside wall at the point of entry to a building contributes directly to building entry loss. But of course radio waves will also reflect from, and penetrate through, internal building walls. Here again the electrical properties of the wall materials have a direct bearing on the reflected and transmitted components of the signal. But whereas the ohmic heating due to the lossy nature of the materials produces signal attenuation, the reflected and transmitted components from multiple encounters with walls will give rise to multipath effects, and even waveguide effects where long corridors and low loss reflections occur.
As is the case with oscillatory behaviour of compound materials, the detailed pattern of multipath effects is a phase effect that is sensitive to the precise geometry of internal building structure on the wavelength scale. As this level of detail will not be captured in simple empirical models of building entry loss, multipath is ignored except insofar as it contributes to the standard deviation of the loss.

### 4.1.2 Diffraction and scatter

Diffraction of radio waves occurs where two different materials meet, or where there is a sharp change in the shape of the surface of a material. Practical examples in buildings are at corners and edges where two or more walls/ceilings meet, and at the edges of window and doors where wood or glass panels meet walls.

Diffraction is generally a “weaker” mechanism than transmission for getting radio signals into a building. On the other hand it can be the dominant mechanism for providing coverage at certain location inside a building. An example would be when a receiver is located close to a highly attenuating exterior wall (metal, for example) when there is an adjacent window. The signal diffracted from the window frame to the receiver may well be much stronger than the signal reaching the receiver directly through the wall.

The strength of a diffracted signal depends principally on the path geometry, shape of the diffracting edge and frequency. It also depends to some extent on the electrical properties of the material comprising the diffracting edge, but this dependence is generally weaker than the other factors. Some computational models assume a perfectly conducting edge for simplicity. In considering the electrical properties of materials, diffraction does not introduce new requirements—the dielectric properties of the material fully describe the material.

Scatter occurs when a radio wave impinges on a rough surface. Whether a surface appears rough or smooth at radio frequencies depends on the relative sizes of surface irregularities compared to the wavelength, and on the angle of incidence of the radio wave. If the irregularities are less than a tenth of a wavelength the surface can be considered smooth at all angles of incidence. At the frequencies of relevance to this study, most internal and external walls can therefore be considered as smooth, and the effects of scatter will be negligible.

On the other hand, building “clutter”, such as furniture and people, can often be modelled as scatter sources as their dimensions are much greater than the roughness of building materials. A few computational models have included clutter, but again a very detailed model is needed to take account of it. The mechanism is quite weak as rough surfaces scatter energy in all directions. The accumulation of scattered components does of course add to the standard deviation of simple prediction models. There are no additional material property issues with the scatter mechanism; when modelled, scatter is generally integrated with the modelling of reflection, absorption and transmission in a way that guarantees conservation of energy.
4.2 Dielectric properties of building materials

In this section we are concerned with characterising the dielectric properties of homogeneous materials. The effect of compound building materials on the attenuation of radiowaves is readily derived from the electrical properties of the homogeneous constituent parts.

Only a brief discussion of the physics underlying material permittivity is given. A more detailed, readable account is given in [2.3]. The fundamental quantity of interest is the electrical relative permittivity, \( \varepsilon_r \). “Relative” means that it is measured relative to the free space value \( \varepsilon_0 \), and is a dimensionless quantity. \( \varepsilon_r \) is a complex number, the imaginary part being responsible for absorption of radiowaves by the material:

\[
\varepsilon_r = \varepsilon_r' + j\varepsilon_r''
\]

At the molecular and atomic level, permittivity is caused by the polarisation of the charge carriers in the material in response to an applied electric field. Several different mechanisms occur, at different scales in the material. For example polar molecules such as water have a permanent dipole moment which causes the dipole to rotate slightly from its rest position in an applied electric field. When the electric field is removed, the molecule “relaxes” back to its normal state. In an applied radio frequency field, the molecules will oscillate. The oscillation is lossy, giving rise to the ohmic losses in the material.

Figure 3.3 shows graphically how different molecular and atomic processes contribute to the real and imaginary parts of the relative permittivity, as a function of frequency. The ionic and dipole mechanisms are the main causes of permittivity at frequencies well into the millimetre-wave region for most common building materials. The contribution of atomic and electronic mechanisms is relatively weak at radio frequencies.

![Figure 4-3: Frequency response of dielectric materials (from [2.3])](image)

Each mechanism has a natural frequency of oscillation, and like a forced pendulum, its response depends on this natural frequency relative to the applied RF field. Figure 4-3 illustrates that the real part of the permittivity due to dipolar oscillation is fairly constant
up to a “cut-off” frequency above which the dipoles stop oscillating and the mechanism stops contributing to the permittivity of the material. For water this frequency is 22 GHz, and for most common building materials is at least 10 GHz.

Figure 4-3 also shows that the imaginary part of permittivity has a peak at the cut-off frequency, corresponding to a peak in attenuation rate of the material. Below the cut-off frequency, the imaginary part of permittivity can be less constant with frequency than the real part, but generally varies fairly slowly with frequency. At the lowest frequencies ionic conductivity effects in moist materials is responsible for a rise in $\varepsilon''$, and hence attenuation, following a 1/frequency curve. The ionic effects are generally negligible at the frequencies of interest in this study.

In the measurement literature, and in ITU-R documents (for example [2.1] and [2.6]) material properties are often given in terms of the real part of relative permittivity and the conductivity. A detailed derivation of the relationship between the various electrical parameters, and practical formulae for their use, is given in [2.1] based on work carried out for Ofcom as reported in [2.4] and [2.5]. Here we give a brief summary of important relationships used later.

Conductivity, $\sigma$, is simply related to the imaginary part of $\varepsilon''$. The definition of the complex permittivity in terms of $\sigma$ is:

$$\varepsilon' = \varepsilon' + j \frac{\sigma}{\varepsilon_0 \omega}$$

$\sigma$ is not dimensionless, but is given in units of Siemens per metre (S/m). Comparing this expression for $\varepsilon''$ with the previous one gives a simple conversion from $\varepsilon''$ to $\sigma$:

$$\sigma = 0.05563 \varepsilon'' f_{GHz} \quad \text{(S/m)}$$

Eq. 4-1

Compared to $\varepsilon''$, the frequency dependence of $\sigma$ contains an additional linear term, so that for most building materials at the frequencies of interest, $\sigma$ increases approximately linearly with frequency.

There are several other ways of quantifying the effects of permittivity in the literature, and measurements are often reported in terms of related quantities such as refractive index, loss tangent and the Q of the material. The key thing is that it is always possible to convert the measurement results to values of $\varepsilon'$ and $\sigma$ (assuming that the frequency of measurement is known), and this allows us to compare different sets of results in a uniform way.

Finally two useful practical formulae give the rate at which radiowaves are attenuated as they pass through a material. The expression for a general dielectric is a little complicated, but a more direct evaluation is possible in the two limits of $\sigma \to 0$ (dielectric limit) and $\sigma \to \infty$ (good conductor limit)\(^7\):

\(^7\) ITU-R Recommendation P.2040 equation (27) contains an error in the expression for the attenuation rate of a dielectric. The expression given here restores the missing square root sign in the denominator.
\[ A_{\text{dielectric}} = 1636 \frac{\sigma}{\sqrt{\epsilon'}} \text{ dB/m} \quad \text{Eq. 4-2} \]

\[ A_{\text{conductor}} = 545.8 \sqrt{\sigma f_{\text{GHz}}} \text{ dB/m} \quad \text{Eq. 4-3} \]

\( \sigma \) is given in S/m. The limits of validity of these expressions are given in [2.1]; they are valid for the building materials of interest in this study. \( A_{\text{conductor}} \) is closely related to the skin depth, \( \Delta \), in a metal (\( \Delta = 8.686 / A_{\text{conductor}} \)).

### 4.3 Metals

All normal metals used in buildings have exceedingly high conductivities (between \(10^6\) and \(10^8\) S/m) and therefore strongly attenuate radio waves. For all practical purposes large metallic structures, such as steel beams and radiators, can be regarded as perfect reflectors and perfect attenuators at the frequencies of interest. However modern building materials incorporate thin metal films, for example foil-backed insulation boards and metallised low emissivity glass, and these may still allow significant RF to pass through.

The conductivity of some common metals is given in Table 3.1. The value for steel depends on composition.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Conductivity x 10^6 S/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>60</td>
</tr>
<tr>
<td>Aluminium</td>
<td>35</td>
</tr>
<tr>
<td>Iron</td>
<td>10</td>
</tr>
<tr>
<td>Tin</td>
<td>9.2</td>
</tr>
<tr>
<td>Lead</td>
<td>4.6</td>
</tr>
<tr>
<td>Steel</td>
<td>1–7</td>
</tr>
</tbody>
</table>

It is not usual to ascribe frequency dependence to a metal’s conductivity as is done for dielectrics. The frequency dependency of attenuation in a metal arises through the skin depth response to an alternating current. Eqn (4.3) shows that the attenuation rate of a metal is proportional to the square root of frequency and conductivity.

Special consideration needs to be given to extremely thin metallic films, such as are found on metallised windows for heat insulation purposes. For example one commercial product uses a 9nm silver layer sandwiched between protective dielectric layers. The
attenuation of these layers caused by ohmic effects will be negligible. But on the other hand the extremely high conductivity of metals can lead to Fresnel reflection coefficients very close to 1, even for thin films. This high reflectivity gives rise to significant transmission loss yielding effective attenuations of tens of decibels, although the precise value depends on angle and polarisation as well as frequency. Calculating the loss due to multilayered metal/dielectric films is quite complicated. There are “multiple dielectric slab” models in the literature but most make simplifications that are not valid for thin metallic films. These are not pursued here.

4.4 Magnitude of attenuation by building materials

Before reviewing the literature of the measurement and modelling of electrical properties of building materials, it is useful to illustrate the magnitude of the effects to be expected. These are based on the table of materials properties in ITU-R Recommendation P.2040 [2.1] from work funded by Ofcom [2.4].

Figure 4-4 shows the frequency dependence of the attenuation rate of a number of building materials calculated using eqn (4.2). The result for brick is probably anomalous (see the discussion in Section 4.6.1 below): by assuming a similar slope as concrete, and anchoring the curve somewhere between 2 and 5 GHz, it would give results between wood and concrete.

![Figure 4-4: Calculated attenuation rates of building materials](image)

Comparing these curves is rather meaningless as the different materials will normally be used in different thickness of sheets. Figure 4-5 shows the predicted attenuations of sheets of material of typical thicknesses. Concrete and (probably) brick walls are thickest and give the highest attenuation. 6mm glass is the thinnest and gives the lowest attenuation. This is much as expected, although the magnitudes may be less than expected. However in estimating total propagation loss through a building wall, a link budget must take account of several factors:
Loss = (sum of individual panel losses at normal incidence) \times \sec(\text{incidence angle from normal} + \text{Fresnel reflection loss})

For a double cavity brick/concrete wall plus a plasterboard sheet, the predicted wall penetration loss at 1 GHz is in the range 3-10 dB. This is comparable with typical measured "shallow" penetration losses. Of course other mechanisms may also contribute, such as the effects of metallic objects.

![Figure 4-5: Calculated attenuation of a sheet of building material (thickness of sheet in mm given in legend)](image)

The frequency dependence of the attenuation rate of the metals listed in Table 4.1 is shown in Figure 4-6. Note that the rates are given in terms of dB/micron (\(\mu\)m).

![Figure 4-6: Calculated attenuation rates of metals](image)

It is clear that even thin aluminium foil (standard household foil is typically 16\(\mu\)m or 24\(\mu\)m thick) will be an impenetrable barrier at all except the lowest frequencies of interest. On
the other hand the films on metallised glass are much thinner, for example 9nm for silver and 300nm for metal oxide layers. Ohmic losses will be negligible, but as discussed in the previous section losses due to Fresnel reflection can be tens of decibels. The precise composition and thickness of metallised layers is clearly important in determining their impact on RF.

4.5 Measurement of dielectric constants

Various methods of measuring the electrical constants of building materials have been used. Each method has pros and cons, such as accuracy, cost of equipment, bandwidth of measurements, limitations on material types, etc. A good summary of measurement techniques (not specific to building materials) is given in [2.3]. Here we focus on the methods generally used for building materials.

4.5.1 Free space methods

These most closely resemble a radio propagation measurement. A parallel-sided slab of material to be measured is placed between a transmitting and a receiving antenna (Figure 4-7). When the angles between the antennas and the slab are set appropriately, the Fresnel transmission and reflection coefficients are measured directly.

This appears to be a straightforward method that requires little in the way of equipment. However many issues need to be considered for good results.

- Careful calibration of the system is required to derive absolute figures
- Even with high gain antennas and large slabs of material, spurious reflections need to be minimised from other materials illuminated by the sidelobes of the antennas. Making the measurements in an anechoic chamber is highly desirable. An alternative, or additional, method is to make time-gated measurements to isolate the wanted signals from the longer-delayed unwanted reflections.
- While the magnitude of the Fresnel transmission and reflection coefficients can be obtained using simple continuous wave power measurements, better results can be obtained using a vector network analyser. This not only
provides phase as well as amplitude information for the S-parameters\( S_{21} \) and \( S_{11} \), but provides results over a range of frequencies.

In order to derive a good estimate of the electrical parameters (relative permittivity and conductivity) from the reflection coefficients or S-parameters, an inversion process and multiple measurements are generally required.

The Fresnel coefficients can be expressed as functions of complex relative permittivity, frequency and incident angle. A popular approach is to measure the Fresnel coefficients at a number of incident angles. Deriving the permittivity from these measurements amounts to solving a set of non-linear, overdetermined set of equations. This can be done using iterative methods to minimise a least-squares estimator of error. This method can give good estimates of \( \varepsilon_r \), particularly when a well-defined Brewster angle\(^9\) effect occurs for perpendicular polarisation, but is less sensitive to variations in \( \sigma \) when the value of \( \sigma \) is small (that is, a good insulator).

An alternative method\([2.7]\) makes use of the transmission coefficient only, at normal incidence, but using a pair of slabs with a variable gap width between the slabs. It was shown in Section 4.1.1 that the transmission loss of a multiple layered material oscillates when plotted as a function of frequency or incidence angle. It also oscillates as a function of the layer thicknesses, and in this method the variable is the distance between the two slabs. The geometry is akin to double glazing with a varying air gap. The permittivity is derived in a similar way to the angle-varying method.

A big advantage of free space methods is that they can be used to directly measure the attenuation of compound building materials. For compound materials the Fresnel coefficients can still be inverted to yield “effective” values of permittivity and conductivity—the values of an equivalent homogeneous material that would give the same Fresnel coefficients. However these values of effective electrical parameters are of little use as they are angle-dependent for a compound material and may be unphysical (for example, may have negative values).

### 4.5.2 Waveguide insertion methods

In this method a small sample of the material is trimmed and tightly fitted into a waveguide section. A vector network analyser (VNA) is used to measure the S-parameters \( S_{21} \) and \( S_{11} \), from which the electrical constants are derived. The hardware and analysis software for this method are often available commercially as add-ons to a VNA.

Assuming that the appropriate equipment is available, the method is straightforward and fast, and has the advantage that measurements can be obtained over a range of frequencies without needing to re-configure the measurement setup. As the sample is

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\(^{8}\) ‘S-parameters’ characterise the behaviour of electrical networks; \( S_{21} \) gives the gain through the network while \( S_{11} \) gives the reflection coefficient of the input to the network.

\(^{9}\) the angle of incidence at which minimum reflection occurs from a boundary between two media.
isolated within a waveguide, this method avoids the contamination due to the surrounding environment present in free space methods.

The measurement accuracy depends on how accurately the material can be cut and fitted into the waveguide, and on the care with which the system is calibrated. Because the samples are relatively small, the attenuation in low loss materials will be small, and the accuracy of derived conductivity may be poor. At the higher microwave and millimetre-wave frequencies the method becomes impractical due to the small size of sample required (a few millimetres): apart from the manufacturing difficulties, inhomogeneities in building materials like brick will give rise to variability between samples.

4.5.3 Other methods

Other methods are available, but are not commonly used for building materials at the frequencies of interest:

- The resonant frequency and Q of a resonant cavity will change if a dielectric sample is inserted in the cavity. This can give high accuracy results but requires very small samples and only gives results at one frequency
- The capacitance of a parallel plate capacitor depends on the dielectric between the plate. In principle a measurement of the impedance of such a capacitor should give the permittivity and conductivity. The method can be accurate, but only works for thin, flat sheets and at low frequencies.
- An open-ended coaxial probe can be used to estimate the permittivity of liquids and powders. The probe is immersed in the material and the reflected signal ($S_{11}$) measured. The accuracy is limited.

4.6 Review of published results

This review includes published results for the electrical constants of building materials at the frequencies of interest, approximately 100 MHz to 5 GHz. There are fewer primary sources, written by the people who made the measurements, than one might wish. A number of sources are “secondary” in that tables of material properties are provided, but the primary sources are not always referenced.

The literature on the electrical characteristics of building materials is largely concerned with measuring the dielectric properties of homogeneous materials. There is almost nothing on the properties of compound materials and little on the loss due to “whole wall” properties, as opposed to “whole house” building entry loss.

The references have all been previously reviewed in two secondary sources.

4.6.1 Ofcom project SES-2005-08 (2007)

Work done by one of the current authors within this project [2.4] reviewed the primary and secondary sources available at the time, and derived parametric fits for the frequency dependence of the electrical properties of a number of building materials.
These results have now been incorporated into the relevant ITU-R Recommendations [2.1], [2.8]. The source material is reviewed in the subsections below.

The study used detailed ray trace modelling and 3D building databases to predict coverage and interference involving the indoor-outdoor interface. Simple formulae were needed to give the frequency-dependence of building materials in the range 1-10 GHz. As these did not exist at the time, work was undertaken [2.5] to derive such a model from published measurement results. We give the formulae and some further information about the building materials that are not available in the ITU-R documents\textsuperscript{10}.

In the literature, the precise nature of a building material is rarely specified. Sometimes qualifiers are given. For example the material identified as “concrete” was either unqualified, or variously described as “lightweight”, “light”, “one year”, “40 years”, “aerated” and “30mm”. Most references only give results at one or two spot frequencies. So in order to have enough samples of a given material to derive a frequency-dependence, it was necessary to group the materials into fairly broad categories. For example, all the concrete types were grouped together in a single “concrete” category, giving 12 samples.

Figure 4-8 shows the electrical constants of the “concrete” samples. The permittivity has a fairly wide scatter (a factor of 4), but no obvious frequency trend. On the other hand the conductivity, drawn on a log-log scale shows a definite trend with frequency. The line fitted to the conductivity data shows that it is approximately linear with frequency, as would be expected if the imaginary part of the permittivity were approximately constant (Eq. 4-1). The scatter in the permittivity values is unfortunate as it gives rise to a factor of 2 uncertainty in the calculated attenuation rate (Eq. 4-2), but this is a consequence of lumping together different types of concrete. All the other materials investigated showed less scatter than for concrete.

\textbf{Figure 4-8: Relative permittivity and conductivity for concrete}

The model for the frequency dependence of the material constants is simply stated:

\textsuperscript{10} Note that the results published in the ITU-R Recommendations [3.1] and [3.8] differ slightly from the results in [3.4] and [3.5] as more data became available during the review process within ITU-R WP3K. The results shown here use the ITU-R values.
Relative permittivity is a constant, independent of frequency; it is the mean of all the measured values for that material.

Conductivity is given by the formula \( \sigma = c f^d \) (S/m) where the constants \( c \) and \( d \) are given by the data fit illustrated in Figure 4-8.

Table 4.2 gives the categories of building material, the number of samples (including multiple frequencies) of each material type, the approximate frequency range covered by the samples (often sparsely), and the fitted parameters for the material’s electrical constants.

**Table 4.2: Building material model parameters**

<table>
<thead>
<tr>
<th>Material class</th>
<th>No. of samples</th>
<th>Frequency range</th>
<th>Relative permittivity</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GHz</td>
<td>c</td>
<td>d</td>
</tr>
<tr>
<td>Concrete</td>
<td>12</td>
<td>1-100</td>
<td>5.31</td>
<td>0.0326</td>
</tr>
<tr>
<td>Brick</td>
<td>4</td>
<td>1-10</td>
<td>3.75</td>
<td>0.038</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>14</td>
<td>1-100</td>
<td>2.94</td>
<td>0.0116</td>
</tr>
<tr>
<td>Wood</td>
<td>14</td>
<td>0.001-100</td>
<td>1.99</td>
<td>0.0047</td>
</tr>
<tr>
<td>Glass</td>
<td>15</td>
<td>0.1-100</td>
<td>6.27</td>
<td>0.0043</td>
</tr>
<tr>
<td>Ceiling board</td>
<td>5</td>
<td>1-100</td>
<td>1.5</td>
<td>0.0005</td>
</tr>
<tr>
<td>Chipboard</td>
<td>3</td>
<td>1-100</td>
<td>2.58</td>
<td>0.0217</td>
</tr>
<tr>
<td>Floorboard</td>
<td>4</td>
<td>50-100</td>
<td>3.66</td>
<td>0.0044</td>
</tr>
</tbody>
</table>

There were in addition, a few samples of other materials (fibreglass, particle board, thermolite, stone, marble and tiles) for which the number of samples was too small to make a model fit. The reviews of the primary sources below give more details of the types of material and frequencies measured. However some of the material names need clarification:

- “Wood”: when qualified, these were genuine natural woods e.g. mahogany, but includes plywood (Douglas fir)
- “Ceiling board”: four of the five samples were qualified as “rock wool”, presumably referring to the resin bonded slabs made by the manufacturer of that name rather than cavity wall/roof insulation

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The values of the parameters are tabulated to 3 or 4 significant figures to maintain accuracy in calculation. The measurement accuracy is generally much poorer than this, with conductivity often given to only one significant figure.
“Floorboard”: three of the four samples were qualified as “synthetic resin”, presumably medium density fibreboard (MDF)

The values of the frequency slope parameter, $d$, are generally close to 1 as would be expected if the imaginary part of the permittivity were approximately constant. The value for brick was set to zero simply because the 4 data points (one at 2 GHz and three at 5 GHz) could not be fitted to the “model”. It would be worth while trying to refit the data by making the assumption that the imaginary part of the permittivity is actually constant. The conductivity would then be strictly linear in frequency, and it would be possible to give electrical parameters as a function of frequency even for those material types for which there is only one or two points. This could be investigated in the current study.

The following sources of material properties were identified. All of the data values (except for particular instances which are noted) were used. All sources that might reasonably be expected to describe the same material (for example, “glass”) were taken together under that label, bearing in mind that the propagation modeller is unlikely in any case to know what kind of glass or plasterboard, etc, is being used.

Because some of the references are secondary sources it is possible that there is a degree of duplication of sources within the references, so that the same original measurement is included in more than one reference. In only one or two instances was a very close match of electrical constants observed for a given material. Indeed the spread of parameters for the same material and frequency was usually quite large. For this reason equal weight was given to all reported values, except where values have been omitted altogether for a good reason.

4.6.1.1  ITU-R Recommendation P.1238-4, Table 7 (2005)

This table gives the complex permittivity for “interior construction materials”, and is identical to Table 8 of the current version (2012) of this Recommendation [2.8]. As with all ITU-R Recommendations, the source of the information is not given, but the values are stated to be derived from measurements apart from the values for glass which are based on a set of equations given in the Recommendation.

7 materials are included: concrete, lightweight concrete, floorboard (synthetic resin), plaster board, ceiling board (rock wool), fibreglass and glass. The measurements were made at 1, 57.5, 78.5, 95.9 GHz although not all materials were measured at all frequencies. In total there are 16 data points, excepting the values for glass. These measurement results were used in deriving the model parameters of Table 4.2.

For glass, a tabulation of the real and imaginary parts of refractive index in the frequency range 0.1–963 GHz was used. This table [2.9] was compiled from 8 sources (25 data values), and was submitted by the Japanese delegation in support of an empirical formula [2.10] for the complex permittivity of glass. This formula, and the much simpler linear fit of Table 4.2 (which also used the values in [2.9]) give almost identical results. Of the primary sources, the only one relevant to the frequencies of interest in this study is [2.11].
4.6.1.2  Pinhasi et al (2005)

This source [2.12] gives the complex permittivity, conductivity and the loss tangent for 10 materials. The frequency was 5 GHz. The materials were concrete (one year), concrete (40 year), brick wall, brick (chalk with holes), brick (without holes), plasterboard, wood (2 values), glass, chipboard.

4.6.1.3  COST 231 Final Report, Table 4.7.4 (1999)

This source [2.13] is a compilation of complex permittivity values for 8 materials for use in indoor propagation modelling. The table values are derived from 3 sources [2.14],[2.15],[2.16]. The frequency was not given but from the context the modelling was relevant to ~2 GHz. The materials were concrete, light concrete, brick, plasterboard, particle board, wood, glass and “bookshelf”. 11 data values were given as the two different modelling approaches sometimes used different values of the constants

Reference [2.15] is particularly interesting as the authors addressed the issue of water absorbed in the cavities in concrete, mortar, hardened cement paste and brick. These measurements were made at wavelengths of 10, 3.3 and 1.25cm so there is some ambiguity about the frequency relating to Table 4.7.4 of COST 231.

4.6.1.4  COST 231 Final Report, Table 8.2.1 (1999)

This source [2.13] reports new measurements of the real part of relative permittivity, loss tangent, attenuation rate, and the magnitudes of the reflection and transmission coefficients of 11 materials at “mmw”, taken from the context to be 60 GHz. The materials were stone, marble, concrete, brick, aerated concrete, tiles, glass, acrylic glass, plasterboard, wood and chipboard.

The measurements were made using the free space method with pairs of slabs described in Section 4.5.1 as proposed in [2.7]. For most materials, two values of the constants are given: "ranges of variation are given each time more than one value has been obtained, either because different polarizations were used, or because they correspond to the results of different groups." Both values were used in deriving the model parameters of Table 4.2.

The values were claimed to give good agreement with others presented in the literature, for example [2.17].

Chapter 8 of [2.13] gives further references to 60GHz measurements.

4.6.1.5  rcafe website

This source [2.18] gives a table of the real part of relative permittivity and the loss tangent of a large number of materials, including building materials. Frequencies range from 1 MHz to 10 GHz. Values for Douglas fir plywood and mahogany at 1 MHz and 3 GHz, wood at 100 MHz and 3 GHz and Corning 7059 glass at 10 GHz were used in deriving the model parameters of Table 4.2.
4.6.1.6 matweb website

The source in Section 4.6.1.5 also links to a huge list of materials giving the values of a large range of material properties [2.19]. For some materials, “dielectric constant” is given, but this appears to include only the real part and the frequency is unspecified (presumably a DC value).

The materials are mainly chemicals and there are few normal building materials. The data were not used in deriving the model parameters of Table 4.2.


This source [2.20] is a study of indoor propagation at 17 and 60 GHz carried out for the Radiocommunications Agency. Table 4 of the reference gives complex refractive index, the real part of relative permittivity and the loss tangent for 5 materials at 17 and 60 GHz: meshed glass, clear glass, plain wood, plasterboard, and thermolite block. An interesting feature of this work is that results are also given for various multiple sheet combinations.

The measurements were made using the free space method, measuring the Fresnel reflection coefficients as a function of angle, described in Section 4.5.1. Values of conductivity derived from this reference were found to be significantly lower than the values obtained from other references and the estimates of conductivity from this reference were not used in deriving the model parameters of Table 4.2.

4.6.1.8 Sato et al (1997)

Table 1 of [2.20] is taken from this reference [2.21]. The complex permittivity of 5 materials were measured at 60 GHz (60 GHz according to [2.20] but strictly 57.5 GHz [2.21]). The materials, concrete, floor board, plaster board (9mm and 12mm) and ceiling board, were used in deriving the model parameters of Table 4.2.

4.6.2 Real Wireless study on award of 800MHz and 2.6GHz spectrum

This large report [2.22] contains an annex (Annex A) on “Propagation losses into and within buildings in the 800, 900, 1800, 2100 and 2600 MHz bands”. This annex includes an extensive literature review and a tabulation of results of measurement campaigns. While most of these refer to “whole building” entry loss measurements, a few of the references relate to the measurement of building materials. The latter are briefly described in the subsections below.

4.6.2.1 T-Mobile Hungary (2009)

This report [2.23] includes loss measurements at 900, 1800 and 2100 MHz on individual building materials as well as “whole building” entry losses. The materials were plexiglass, glass, plasterboard (2 layers), brick wall (19cm and 30cm) and metal vapoured glass.

This source document could not be found but a table of losses was reproduced in reference [2.22] Annex A. All losses show an increase with frequency. The loss in glass is ~ 1 dB, while the plasterboard and brick wall losses are in the range 5–15 dB.
Of particular interest is the result for "metal vapoured glass" as this is the only reference found to measurements on metallised glass. The losses at the 3 frequencies were 18, 25 and 28 dB, respectively.

4.6.2.2 Stone (1997)

This is an extensive report [2.24] on the characterisation of the electrical properties of building materials. The focus was on the power attenuation as a function of material thickness. A second report on the values of the electrical permittivity and dielectric constants for a particular material as a function of frequency was planned. Measurements of power loss were taken at 2 MHz intervals from 0.5 to 2 GHz and from 3 to 8 GHz. A free space measurement method was used using a vector network analyser and time domain gating.

The building materials included brick, masonry block, eight different concrete mixes, glass, plywood, lumber (spruce-pine-fir), drywall, reinforced concrete, steel reinforcing bar grids, variations of the plywood and lumber tests in which the specimens were soaked with water, and composite specimens involving brick-faced masonry block and brick-faced concrete. For each material, varying thickness specimens were fabricated in order to measure attenuation as a function of penetration distance.

This report is particularly detailed in its description of the composition of the building materials used and is worth further study. Of particular interest are the results for the compound materials, for example brick-faced concrete and reinforced concrete.

One oddity is that in the 3 to 8 GHz range the attenuation often decreased at the higher frequencies, or showed the beginning of oscillatory behaviour when plotted as a function of frequency. Further study is required to see whether or not this is the results of resonant effects in the materials.

4.6.2.3 Virginia Polytechnic (2002)

This study [2.25] was carried out in support of the development of ultra wideband communications. Free space time and frequency domain measurements were carried out over a frequency range of 1–15 GHz.

Commonly used building materials were included: wallboard, structure wood, glass sheet, bricks, concrete blocks, cloth office partition, wooden door, plywood and styrofoam slab.

Tables are presented showing, for each material, the loss and dielectric constant as a function of frequency. For the homogeneous materials (structure wood, wooden door, and plywood) the attenuation rate (dB/m) is also given.

4.6.2.4 Wilson (2002)

This study [2.26] was focussed on comparing WiFi performance at 2.4 and 5 GHz. A large set of 20 building and furnishing materials were included: plexiglass, blinds, red brick, carpet, ceiling tile, fabric, fibreglass, glass, drywall, light cover (for fluorescent light bays), linoleum, fir lumber, particle board, plywood, tiles, tar paper, cinder block, diamond mesh, stucco and wire lath.
The measurement method was the free space technique in an anechoic chamber, using a vector network analyser swept from 1–12 GHz. For each of the materials, the real part of relative permittivity and the loss tangent were derived from the measured scattering parameters in the frequency range 2–7 GHz. The permittivity and loss tangent were assumed to be independent of frequency.

4.6.2.5  *Gibson and Jenn (1999)*

This study [2.27] is largely a theoretical approach to modelling the loss through a panel based on the Fresnel reflection and transmission coefficients. However the model was validated using new free space measurements of the loss through various materials and taking values for the electrical parameters of the material from handbooks. Graphs of the losses due to a concrete wall, a wood door and a metal door are shown over the frequency range 2–6 GHz.
5  **EFFECT OF BUILDINGS ON PROPAGATION**

This section reviews material relating to measurements of the overall effect of buildings on radiowave propagation. Here the small-scale details of construction materials and the physical mechanism by which electromagnetic waves penetrate building are generally ignored in favour of a statistical characterisation of the bulk effect. Such measurements have generally been carried out either to determine a statistical characterisation of building loss that can be used directly in link planning, or in support of the development of more sophisticated models such as those involving ray tracing. A recent survey [3.4] for Ofcom by Real Wireless covers this topic very well, but is concerned with a narrower range of frequencies (800 MHz to 2.6 GHz).

5.1  **The physics of radio wave propagation into buildings**

As noted in [3.4], propagation into buildings can involves a large number of paths and different mechanisms that may offer opposing trends of attenuation versus frequency.

One example, particularly relevant to the present study, is that longer wavelengths may suffer less absorption due to building materials, but may not couple easily through available apertures such as windows or doors. This may be particularly relevant for the 100 MHz and 200 MHz broadcast bands where the wavelength is comparable with typical aperture sizes.

Another complicating factor, that mitigates against simple models for building loss, is that penetration into buildings will often involve multiple paths (e.g., through walls, diffracting around window frames, penetration through thin roofing material and down through wooden floors). This characteristic may cause the overall building entry loss (BEL) to be a very complicated function of the arrival angle of the wanted signal.

Many of the studies examined note the difficulty of separating the characteristics of building loss from the clutter around the building. The effects of neighbouring buildings are often cited in the literature as the cause of anomalies in the trend of BEL with height.

5.2  **Definitions**

Terms such as ‘building loss’ or ‘penetration loss’ are often used in link budgets without any precise definition. In any survey of measurements reported in the literature, however, we must be confident that the individual result are directly comparable. In practice, the definitions used, and the measurement methods employed are found to vary quite widely.

In the present work we have consciously adopted the term ‘building entry loss’, the alternative term, ‘penetration loss’ is potentially ambiguous, as it might refer to the loss experienced by a terminal passing behind a building (but remaining outdoors).

5.2.1  **Building entry loss**

ITU-R Recommendation P.1406 quotes a definition of building entry loss as “the difference between the signal measured outside the building at street level and that measured inside the building”.
P.1411 and P.1812, on the other hand, state that "Building entry loss is the excess loss due to the presence of a building wall (including windows and other features). It is defined as the difference between the signal level outside and inside the building at the same height". The definition given in the new Recommendation, P.2040 is essentially the same, but more precisely drawn: ("The building entry loss is the difference between the spatial median of the signal level outside the illuminated face of a building and the signal level inside the building at the same height above ground, with multipath fading spatially averaged for both signals.").

The recent survey by Real Wireless notes that the definition chosen by Ofcom is: "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 definition appears to ignore the fact that buildings have an extent; although it may be sufficient to talk about 'the median [...] at the building location' in the context of predictions using a 50m or 100m resolution database, it is not helpful when conducting field measurements.

The Real Wireless survey also notes that Ofcom explicitly separate the ‘building penetration loss’ from the ‘internal penetration loss’, with the latter being given by the product of the ‘internal penetration distance’ (presumably with respect to the illuminated wall) and an ‘internal loss coefficient’.

This seems a useful formulation, responding to a need to express link budget margins in terms of the degree of penetration within a building that they allow. Unfortunately, very little measurement data seems to have been reduced to this form.

In determining a useful definition of ‘building loss’ there is a tension between quantities that can readily be measured and those that are of use to the planner.

For planning purposes it is generally possible to predict the median outdoor field strength to any point in 3-dimensional space\(^\text{12}\), and building loss can then be expressed as an additional loss to be subtracted (in dB) from that field. As the outdoor prediction can easily be made to the relevant storey of the building the ‘Ofcom’ definition can apply. Determining the correct value of internal penetration distance to select may be more difficult, as potentially-serving transmitters may exist on either side of the building (implying that the required penetration is half that for a single transmitter).

If undertaking measurements, it may be challenging to determine ‘the signal level inside the building at the same height above ground’. In [3.10], the authors note that ‘the building […] is predestined for such measurements because of its surrounding balcony’, but such architectural convenience is rare. Most of the empirical studies reported in the literature, therefore appear to use the ‘street level’ reference (e.g. [3.7],[3.8], [3.9]), which

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\(^{12}\) Although many propagation models may restrict the height of one terminal to a point below the nominal street level
has implications when comparing the results with the assumptions made in Ofcom studies.

5.2.2 Variability of loss

Figures quoted for the variability of quoted loss values may also relate to different quantities. In the most reported measurements, the location variability of the signal within a building, or on one floor of a building is given. In some cases, however, it is clear that quoted standard deviations are intended to reflect the variability in entry loss between different buildings, rather than within an individual building.

5.3 ITU-R Recommendations

As a starting point for any survey, it is useful to review the advice given in the formal Recommendations of the ITU-R.

5.3.1 P.2040-0 (“Effects of building materials and structures on radiowave propagation above about 100 MHz”)  

The title of this Recommendation [3.1], already referred to in the previous section, suggests that it should be directly relevant to the work of the present study. Section 1.2 gives the definition of building loss quoted above. Section 4 of the Recommendation summarizes the result of a number of empirical studies, at frequencies between 100 MHz and 6 GHz. No attempt was made in this initial version of the recommendation to collate the data taking account of the specific measurement methods (it is noted in the text that some of the measurements were made in a manner that does not accord with the definition given in Section 1.4).

5.3.2 P.1411-7 (“Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz”)

This Recommendation [3.2] is largely concerned with outdoor propagation, but includes a brief Section 4.5.2 on “building entry loss”. The following definition is given:

“Building entry loss is the excess loss due to the presence of a building wall (including windows and other features). It is defined as the difference between the signal levels outside and inside the building at the same height. Account must also be taken of the incident angle. (When the path length is less than about 10 m, the difference in free space loss due to the change in path length for the two measurements should be taken into account in determining the building entry loss. For antenna locations close to the wall, it may also be necessary to consider near-field effects.) Additional losses will occur for penetration within the building; advice is given in Recommendation ITU-R P.1238. It is believed that, typically, the dominant propagation mode is one in which signals enter a building approximately horizontally through the wall surface (including windows), and that for a building of uniform construction the building entry loss is independent of height”.

A single measurement is quoted, for an office building at 5.2 GHz, with a mean loss of 12dB and a 5dB standard deviation. The concrete and brick wall was 60cm thick, and windows formed a third of the wall area.
5.3.3 P.1238 ("Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz")

This Recommendation discusses propagation within buildings, and material characteristics, in some detail, but is not concerned with entry loss.

Although the Real Wireless survey quotes figures for building entry loss from an old version (-3) of this Recommendation, this is an error as the tabulated values actually relate to floor penetration loss. This table has been expanded in the current version (-7) of the recommendation.

5.3.4 P.1812-2 ("A path-specific propagation prediction method for point-to-area terrestrial services in the VHF and UHF bands")

This Recommendation [3.3] gives a propagation model for relatively long-range outdoor paths at 30MHz to 3 GHz, but includes a brief section (§4.9) on terminal corrections to take account of building loss.

A table is given suggesting that median loss is 9dB at 200 MHz, rising to 11dB at 600 MHz and 1.5 GHz. These figures were originally taken from measurement data submitted by the EBU.

5.4 Review documents

The topic of building loss has been the subject of a number of useful reviews over the last decades. There would be little merit in repeating this work, and the discussion below is therefore largely limited to a meat-analysis of these studies.

One factor common to most of these studies is the focus on commercial, office or academic buildings. It is intended that the measurements made in the present study will concentrate on domestic buildings to a much greater extent.

5.4.1 Real Wireless, 2012

This survey of “Propagation losses into and within buildings in the 800, 900, 1800, 2100 and 2600 MHz bands” [3.4] was commissioned by Ofcom in support of their consultation on spectrum release at 800 MHz and 2.6 GHz.

Section 4 of the document contains a useful summary of the assumptions made regarding building loss in Ofcom publications in recent years. This section notes that “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”.

A particular focus of the Real Wireless approach was to understand the variation of loss with frequency. It is noted that the trend most often observed is for loss to increase with frequency, but that some workers (e.g. in [3.7], [3.8]) have observed the opposite trend, as shown in the figure below.
Figure 5-1: Summary of frequency coefficient variation (From Reference [3.4])

It is commented that, although some of the observed variation may be due to methodological issues, substantial variation would be expected on physical grounds. The paper does not discuss how the trend might be predicted from a knowledge of building structure – this might be an area that the present study could usefully examine.

5.4.2 Bertoni et al, 1994

This review [3.5] of small-cell propagation loss at 800-900 MHz is also referenced in the Real Wireless study, but contains only a brief discussion of building entry loss.

5.4.3 COST 231, 1999

Chapter 4 of the COST 231 Report includes a brief section on Building entry loss [3.6]. This treatment divides penetration loss into:

- Wall loss: Angle-dependant loss through a wall. It is noted that this is hard to measure in a building, due to the presence of multiple reflections and clutter.
- Room loss: The median loss in a room determined from measurements. This is a quantity that has been used in earlier Aegis/Signal Science measurements and probably represents the smallest quantisation of loss statistics that is generally useful.
- Floor loss: The median loss measured across all rooms on the same floor of a building (not to be confused with the same term used to refer to the loss through a floor/ceiling structure).
- Building loss: Median loss across all floors of a building.

The section refers to 14 references from workers associated with the COST231, and presents two simple empirical models, for buildings that are line-of-sight or non-line-of-sight to a transmitter, that claim to reflect the results presented in those papers. It is clear that the parameter values in these models are somewhat vague, A coefficient, corresponding to Ofcom’s ‘internal loss coefficient’ is used, with a value of ‘about
0.6dB/metre. Figures close to this value (0.5 at 900 MHz and 0.6 at 2.1 GHz) were used by Ofcom in the February 2009 consultation referenced in [3.4], but by the time of another consultation in January 2012, the range of the parameter had increased to between 0.32 at 800 MHz to 1.23 at 2.1 GHz. It is not known if there was any empirical evidence for this change.

5.5 Individual experimental studies

5.5.1 Wells, USA, 1977

This study examined the entry loss to 13 rooms within 6 houses in the US. The houses were of light construction (wooden framed with either wooden or brick outer surfaces. The mean loss across frequencies of 860 MHz, 1550 MHz and 2569 MHz was 6.3dB.

This paper is cited in the Real Wireless survey, which noted the frequency dependence of the entry loss, but does not mention that the source for the signals was a geostationary satellite at a relatively high elevation angle.

Although the survey states that the variability of the loss is not given, a value of 1.5dB for the standard deviation of loss within any room is quoted, a figure that did not change with frequency.

Of particular interest to the present study is that the impact of insulating materials was assessed. Where aluminium-backed ‘Sheetrock’ was present, the entry loss was increased by around 11dB.

5.5.2 Toledo, et al, Liverpool, 1992-1998

References [3.7] and [3.8] described measurements made on the campus of Liverpool university and in buildings in Liverpool city centre at 900 MHz, 1.8 GHz and 2.3 GHz.

This was quite an extensive campaign, and is reported in some detail in several papers and a PhD thesis. One noteworthy element is that entry loss was found to fall with increasing frequency.

Reference [3.7] contains some discussion relating to the difficulty of obtaining a representative ‘outdoor reference’ measurement.

5.5.3 Medbo, et al, Stockholm, ~2007

This campaign in Stockholm used CW sources at 460 MHz, 881 MHz, 1.8 GHz and 5.1 GHz. These were mounted on the roof of a 29 metre building, above local clutter. Measurements were made in the corridors of 5 office buildings (including that on which the antennas were sited) at ranges up to 650m.

Measurement results were presented in terms of the excess loss relative to the free space value (see Figure); it is striking that the median values of all measurements align at 30dB, with the exception of those for 5.1 GHz.
The additional loss at 5.1 GHz is attributed to “metallic window coating which attenuates the received signal substantially more at 5.1 GHz than at the other frequencies”.

The paper discusses the relative merit of (i) using outdoor measurements at street level to determine BPL at the ground floor, versus using the predicted LOS field outside upper floors with a clear path to the transmitter to determine losses to those floors. It is noted that the uncertainty in the ‘street level’ reference is significant.

The values of BPL quoted in the Real Wireless paper are the average values for the ground floors of the three most distant of the five buildings studies.

The loss values obtained are rather high, presumably because they were measured in corridors in office buildings typical of dense urban areas. The classification of these results as ‘Suburban Residential’ in Figure 5-3 of the Real Wireless survey is therefore somewhat misleading.

5.5.4 Building loss at broadcast radio frequencies

Part of the motivation for the present study was related to issues of comparative indoor coverage for FM (100 MHz) and DAB ((220 MHz) radio transmissions.

Little data has been found in the literature regarding building entry loss at Band II frequencies, with most recent work concentrating on higher frequencies. One set of measurements [3.14] by the BBC in a number of suburban homes found a median

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13 Although the table in [3.4] refers to 5 buildings
building loss of 13.6 dB with reference to the outdoor field at 10 m (of a vertically-polarised transmitter). The standard deviation was 7.5 dB.

The BBC undertook a survey of building loss in 26 domestic buildings in 1992, using an initial, experimental low-power DAB network, operating with a 1.75 MHz system bandwidth. In these measurements, the field strength at 2 m outside the building, on the side facing the dominant transmitter, was taken as the reference.

The results, given in [3.9] showed an average building loss to the ground floor of 7.9 dB, with a standard deviation of 3.7 dB within a room, or 5 dB across all ground floor rooms.

These results were supplemented [3.15] by measurements made in a further 13 houses, using the pre-operational high-power DAB network. Although made in more urban areas, these measurements gave very similar results, with an average loss of 8.3 dB.

A set of measurements were made in five commercial buildings in central London, and reported on in 2004 [3.16]. In the measurements the aggregate power from an existing SFN was sampled continuously as a trolley-mounted receiver was moved around each floor of the target building. Reference measurements were also made outside the building at ground level.

The overall entry loss values given for each building appear to be the median (or average) values for all data across the floors of interest, rather than the mean of the values for each floor. It is not simple to compare the values across buildings, as some relate to all seven floors of an office block, others only to the first two floors. The study concluded that an ‘average’ building entry loss of 15 dB was an appropriate assumption for the planning of indoor services, coupled with a standard deviation within the building of 5.0 dB.

A substantial survey [3.17] of building loss at Band III and L-band was carried out in Sydney in 2005. Measurements were made in 35 buildings, covering domestic, retail and commercial properties.

The reference for the measurements was established by recording external field strength at ground level on all four sides of the building, from balconies on each measurement floor and on the roof. Details of the data reduction are not made explicit in the report, but it appears that the reference used to define building loss was the largest of the four mean field strengths measured at ground level outside the building. This is, therefore, comparable with the methods in [3.9], [3.15] and [3.16].

The mean loss value, for ground and first floors combined in all buildings surveyed, is 11.1 dB. The value for domestic buildings is much lower at 4.9 dB, while commercial buildings have ‘ground and first-floor’ losses between 13 dB and 17 dB.

The standard deviation of the signals measured inside and outside the building was found to be almost identical, at 4.4 dB and 4.3 dB respectively. The report does not describe the derivation of these standard deviations, however, so it is unclear whether they are average figures for room SD, average figures for building SD or simply the standard deviation of all measurements made in all buildings.
5.6 Commentary and Conclusions

The enormous variability of building loss, as indicated by the figure below, might inspire a certain pessimism as to the possibility of providing any useful, quantitative guidance on building loss.

Figure 5-3: Collated values of BPL (From Reference [3.4])

The situation is not, however, quite as bleak as it may appear. The figure above, and many similar plots in the literature, collate empirical results that are not really comparable.

In this case, loss values are included that were measured to both dense urban office blocks and rural wood-framed houses. Signal sources include test transmitters at a hundred metres range, distant broadcast transmitters and satellites at relatively high elevation angles. Furthermore, the reference against which loss has been defined is taken variously as being at the same height as the measurement, at street level on the illuminated face of the building or the median of the street-level field.

If studies were to be limited in scope to, for example, ‘domestic buildings representative of 80% of UK housing stock’, and if measurements are made in such a way that they can be reduced for comparison with other data sets (e.g. by measuring external fields on all sides of the building and at different heights), the variability of results may be less daunting than it initially appears. For the specific case of domestic buildings, however, such analysis would reveal the very small quantity of empirical data in the literature.

The treatment of variability gives some cause for concern. In some work, standard deviations are given for individual rooms; other works quote values for individual floors or buildings, or the whole data set. It is often not clear how the SD values given in reports are derived.
It seems that, in most cases, the variability quoted relates to that due to shadowing and loss variation as the user moves within the building. These values are often comparable with those measured for location variability outside the building, and it is not clear to the author that there is necessarily any statistical justification for the combination of ‘outdoor’ and ‘indoor’ variabilities as is suggested in, e.g. ITU-R P.1812 in this case.

The ‘variability’ figure that is really required is that relating to the variation in median BPL for all different buildings of interest. This would imply a very substantial measuring campaign.
6  MEASUREMENTS - METHOD

It is evident from the reviews in Sections 4 and 5 above that there has been no shortage
of empirical studies of the impact of buildings and materials on radiowaves. The limited
time and resources available for the present study there needed to be targeted carefully
to achieve more than a trivial addition to an already large data set.

The following areas appeared to merit particular attention:

Extension of measurements to lower frequencies. The vast majority of measurement
have concentrated on the frequencies of most interest to cellular radio operators, at
800 MHz and above. Examination of lower frequencies is important not only because of
the regulatory interest in broadcast coverage issues, but because different physical
effects become significant as the wavelength increases to be of the same order as
elements of the building structure.

Data on domestic buildings. It is often observed that the only buildings that are really well
collected are the those belonging to university engineering departments. It is striking
that domestic buildings form a very small portion of those discussed in the literature. As
such, new measurements of such buildings would have a particular value.

Characterisation of building elements as opposed to small homogenous material
samples or whole buildings. It has proved difficult to produce reliable whole-building
models based on the electrical characteristics of their constituent materials in isolation.
Modelling using composite elements (walls, roofs) may offer a more viable route to
successful modelling.

Before and after measurements with specific ‘upgrade’ materials (insulation, metalised
glass, etc). Measurements have been made of buildings with, and without these
materials, but it is very difficult to separate the variability due to the different buildings
from that due to the materials. The unique facilities at BRE offer a chance to measure the
same building before and after the addition of these materials, or differently specified, but
otherwise identical buildings.

Given the relatively limited time available for the study, it was been decided to focus
largely on measurements relating to one particular building, and to ensure that the
impact of two energy saving construction methods is well understood. A single set of
measurements were also made on a very different building for comparison and
measurements of different energy saving materials were made in an anechoic chamber.

6.1  Measurement method

As the focus of the study was simply on the attenuation offered to radio waves (rather
than for example, multipath characteristics), the equipment requirements are relatively
straightforward.

CW sources are used as the test source, with the only constraint that their location
relative to the building should be representative of the real-world signals of interest. This
implies that a significant separation distance may be necessary in some cases.
For example, if one is interested in the statistics of penetration into a building with a lightly-constructed roof, it might be found that diffraction over the top of the wall facing the transmitter is a significant signal path. The diffraction loss suffered on this route from a handheld transmitter in the street would be very different from that suffered by a signal arriving on a near-horizontal path from some distance away. For the initial measurements at BRE, signals transmitted from within the house were received with transportable antennas (mounted on a Land Rover) at a range of some 32m.

The hardware at the receiving end was simple. The field within buildings is generally multipath-rich, which implies a need for dense sampling, particularly at the higher frequencies. A standard measuring receiver (the Rohde and Schwarz EB200), is used under computer control from logging software developed by Aegis; this logs data in the form of XML files suitable for post-processing.

The most significant complexity in the measurement arrangement will arise due to the wide bandwidth (100 MHz – 6 GHz) to be covered and the need for antennas with well-defined characteristics. In a previous study for Ofcom [3.18], an attempt was made to develop a discone antenna capable of covering a decade range in frequency. In the event it proved difficult to establish a predictable antenna polar response at the upper end of the design band (5 GHz), and a cluster of antennas for the different frequencies was used instead.

Such a cluster would become mechanically and electrically unmanageable for the frequency range of present interest, and has therefore been necessary to make separate measurements for each frequency.

### 6.2 Choice of Frequencies

There is a need to minimise the number of frequencies used (to reduce measurement time and equipment complexity) but also to sample the 100 MHz – 6 GHz frequency span adequately. Although individual buildings and specific geometries may exhibit rapid changes in loss with frequency, the trend, when averaged, tends to have a rather low coefficient of frequency (see Figure 5-1). It is clearly necessary to sample at either end of the range (100 MHz and 6 GHz), and the strategic interest in DAB probably dictates that measurements be made in this band as well. The span from 200 MHz to 6 GHz covers more than a decade and there should probably be two sample points in this range. The final frequencies adopted for the measurements are given in the table below.
Table 6.1: Frequencies proposed for measurement

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>88.4 MHz</td>
<td>Locally-clear channel in FM broadcast band</td>
</tr>
<tr>
<td>217.0 MHz</td>
<td>Locally-unused DAB channel (11A)</td>
</tr>
<tr>
<td>698.0 MHz</td>
<td>Locally unused TV channel (ch.49)</td>
</tr>
<tr>
<td>2410.0 MHz</td>
<td>ISM / amateur allocation</td>
</tr>
<tr>
<td>5760.0 MHz</td>
<td>ISM / amateur allocation</td>
</tr>
</tbody>
</table>

The necessary non-operation licences have been granted by Ofcom.

6.3 Measurement hardware

A set of low-power signal sources have been developed specifically for this study, and these are shown in the figure below. Individual sources are used for 88.4 MHz and 217.0 MHz, while the sources for the higher frequencies are packaged in a single enclosure.

The sources have power outputs of between 30-500mW, and are powered from lead-acid batteries via a DC-DC inverter to provide a regulated supply.

The transmit antennas for the three lowest frequencies were standard dipoles, intended for EMC measurements; sleeve dipoles were used at the two higher frequencies.

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14 EMCO model 3120
6.4 Measurement locations

The initial aim of the measurements was to characterise the impact of foil-backed plasterboard and metalised glass in a relatively simple environment.

The site selected for the majority of the measurements was building B50.2, which is the second building from the left in Figure 6-2 below.

Figure 6-2: B50.2 test houses at BRE

B50.2 is built to the UK Building Regulations (1995) and has levels of insulation to just beyond the 1995 Part L requirements. It has a filled cavity construction (brick/block) and single glazed windows enhanced with secondary glazing.

Access to this building has allowed the following measurements to be made:

- Characterisation of a “standard/typical” whole building construction type, with no exceptional insulation techniques added, and no foil backed plasterboard installed.

- Characterisation of an “upgraded” house with the some or all of the following measured installed for any particular measurements:
  
  o Installation of foil backed plasterboard within the house. This will be done by screwing foil backed plasterboard into the existing walls, and foil taping the joints. The walls already contain non-foil backed plasterboard which cannot be removed, so this will create a wall that has an additional layer of plaster than would not normally be the case\(^\text{15}\).

  o Installation of metallised windows. The house is already fitted with frames into which a set of metalised windows can readily be slotted.

\(^{15}\) Measured values in the literature for attenuation due plasterboard show that this additional layer would have no impact on the results.
Although the time available for measurements was necessarily limited, it was felt that at least one other sample building should be characterised, if only as a reminder of the wide spread of entry loss values likely to be encountered in practice.

Figure 6-3: Wing of mansion used as measurement location

Measurements were therefore made within one wing of the ‘Mansion’ at BRE; the building is in constant use as a meeting venue, however, and it was not possible to experiment with any of the ‘upgrades’ investigated in Building 50.2.

Full details of both locations are given in Appendix C.
7 MEASUREMENT - DATA REDUCTION

7.1 Methodology

The definition adopted for building entry loss (BEL) is based on that used by Ofcom: “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”.

As noted in Section 5, this definition does not specify exactly what is intended by the terms ‘building location’ and ‘inside the building’. We have therefore chosen to adopt a more prescriptive definition in which the signal level ‘inside the building’ is characterised as the median level for each room, and the outdoor ‘reference’ field is measured at a fixed distance from the wall facing the outdoor terminal.

A number of issues arise because buildings are not point objects, but have extent. These effects could impact on the accuracy of the measurements and were investigated by making further measurements or modelling as appropriate. These are discussed below and include:

- the effect of multipath on the reference field in front of the house. This can potentially result in a variation of the reference field with distance from the wall and with height above the ground.
- the effect of the short (32m) propagation path on buildings that have finite extent

7.2 Calculation of indoor and outdoor signal levels

7.2.1 Indoor measurements

Separate measurements were made in each of the rooms or spaces within each house. In each space, the source and antenna was carried in a semi-regular pattern to explore the room in a crosshatch pattern. This approach was found to work well in the earlier In-home Propagation study for Ofcom [3-18]. Criss-crossing the room in one orientation followed by a second pass at right angles to the first ensures that the room is well-sampled, even when the route is partially blocked with furnishings. The centre of the vertical dipole antenna was kept at approximately chest height, although some variation was inevitable, due in part to the house furnishings.

Because of the complex multipath environment, no attempt was made to resolve the multipath or to make individual data points reproducible. The intention was to obtain sufficient data points to calculate a statistical distribution of signal values from which, for example, reproducible room medians can be derived. Depending on room size there are typically between 5,000 and 20,000 data points per room. In any case much of the multipath is caused by the movement of the person holding the antenna [3-18]. As far as possible the antenna was positioned so as not to be obstructed by the body, but there
will inevitably be some attenuation, multipath and (at the lowest frequencies) near-field effects from the person holding the antenna.

For each measurement set, an attempt was made to only change one aspect of the building structure at a time. In all cases, the external doors and windows were closed, and all internal doors were open. In any case earlier measurements [3-18] showed little effect of internal doors on in-building signal propagation. Only the person making the measurements was in the house at the time. The building work required to add the foil-backed plasterboard to the walls necessitated some moving of furniture, but this was restored to approximately the same positions as before.

The time series measurements gathered in each room were processed to determine the cumulative distribution function (CDF) of the signal. The example in Figure 7-2 shows a high level of multipath which results in the asymmetry of the CDF. Various statistical quantities are of interest. As in the earlier study [3-18] the distribution median was used (58.7 dBUV in this case) as the "multipath–averaged" signal level for a room in subsequent analysis of building entry loss.

![Figure 7-1: Time series and CDF for B50.2 living room at 2.4 GHz](image)

7.2.2 Outdoor reference field measurements

The reference field at ground level was established by walking with the calibrated signal source backwards and forwards across the face of the building facing the receiver, at a fixed distance from the wall. In our first sets of measurements, this fixed distance was
1m, but in later measurements we took reference measurements at 1, 2 and 3m from the wall in order to investigate the effect of multipath on the results. The measurements were made at a height of 2m which corresponds to the height at which measurements were made inside the building.

Four passes in front of the building were made in each walk, and the measurements showed a high degree of repeatability on each pass, particularly at low frequencies, as seen in Figure 7-2. For ‘linear’ walks such as this, made at a constant walking pace, the sample numbers are approximately proportional to distance. Strong coherent effects of multipath are clearly visible, particularly at 88 MHz. The four passes in order were right-left, left-right, right-left and left-right. The two halves are virtually identical, while within each half the right-left and left-right traverses are mirror images of each other. Small differences between the right-left and left-right traverses are to be expected from the asymmetry caused by the antenna being held in front-of the body in both directions.

![Figure 7-2: Reference measurements taken at front of house (top=88 MHz, bottom = 5 GHz – note difference in vertical scales)](image)

In order to obtain a single outdoor reference value for the lower floors, it is necessary to ‘spatially average’ the multipath fading, as required by the definition of BEL. We do this using the same method employed for the indoor measurements: the median value of the (typically 7000) data points from each ‘walk’ is used.

Ideally the same approach would have been adopted for the reference measurement for the upper floors, but this was not possible for practical reasons. The reference fields
were therefore established by holding the source antenna out of each of the four upstairs windows in turn and moving it as far as possible in a horizontal plane.

Figure 7-3 shows the median signal values obtained from all outdoor reference measurements in building B50.2 from the initial measurement sets that used identical RF sources. This includes four different building material configurations of the house and multiple-distance outdoor ground level measurements where available.

![Figure 7-3](image)

**Figure 7-3: Outdoor reference measurements for four configurations of building B50.2: D indicates downstairs (blue), U indicates upstairs (red)**

The large differences in signal level at the different frequencies should be ignored: the values are uncalibrated signal levels which depend on transmitter power, antenna gains, etc. These differences are removed later when we calculate building entry loss.

At each frequency the spread of values is generally less than 5dB or so if we consider the upstairs and downstairs groups separately. Even within that relatively small spread there is evidence for the measurements to form clusters corresponding to the different building material types. In each cluster the data represent measurements at 1, 2 and 3m from the wall (downstairs) or measurements at the four windows (upstairs). The variation between clusters could be caused by different multipath environments for the different building configurations, or simply slight differences in the system link budgets—the measurements were made on different days. For accuracy we have used different outside reference field values for each of the building configurations, calculated by averaging the median values of each point in the corresponding cluster.

There is evidence for different reference values at ground floor and upstairs levels. This is clearest at 88 MHz where the ground-reflected multipath lobes are widest. This height-gain effect is discussed further below, but the need to use different outside reference values for the ground floor and upstairs rooms is clear.
7.2.3 Reproducibility

In order to assess the reproducibility of measurements, three rooms were measured at 698 MHz by two different people, about half an hour apart. Both used the crosshatch measurement method, but there was no attempt to follow the same route exactly. The time series for the Living Room are shown in Figure 7-4.

![Time series for the Living Room at 698 MHz](image)

The similarity of the multipath in both cases is remarkable, although clearly there are differences at the small scale. Note the different number of samples in the two cases (20,000 versus 30,000) showing that the two walks were made at different speeds.

The room medians for the three rooms differed by 0.3, 0.7 and 0.3 dB for the two people. It was concluded that the measurements were reproducible to within the measurement errors.

7.3 Calculation of building entry loss

The calculation of building entry loss (BEL) is simple in principle. It is just the difference in decibels between the appropriate reference field just outside the front of the building and the signal level inside the building. As already described the median values of a statistical sample of signal values were used to average out the effects of multipath fading.
However there are a number of issues arising from the lack of precision in the literature on how BEL is defined. In particular there is an implicit assumption that a building has zero extent, so that the signal impinging on the front of the building has a constant value, at least when multipath fading is ‘averaged’ out. There are at least two problems with this assumption. The first is that ground-reflected multipath effects at VHF may produce interference lobes that vary slowly on the scale of a building, so that averaging within a room, or across the face of the building, may not eliminate the multipath effects. Another practical issue arises when the extent of the building is not negligible compared to the measurement path length; in this case signal variation can occur between the front and back of the building due to the non-plane wave nature of the test signal.

7.3.1 Effects of ground-reflected multipath

Reflections of the transmitted signal from any reflecting surface will add multipath components to the received signal. The strongest effects will be produced by large, smooth, planar objects. In the building environment there are plenty of these: walls, floors, ceilings, windows, doors, and the ground in front of the building. All of these are fairly smooth at the frequencies of interest and can give quite strong reflections. In general it is difficult to identify which particular reflectors are contributing to the multipath lobing seen in the data such as the 88 MHz measurements of Figure 7-2. However reflections from the ground in front of the house are of special interest for two reasons:

- In general the path length difference at the building between the direct and the ground-reflected ray is likely to be much smaller than between rays reflected from other obstacles and vertical surfaces. This results in the most widely spaced interference lobes giving rise to the most ‘coherent’ effects seen as distance or height is varied.
- Ground-reflected multipath can produce gradients of signal with height (‘height-gain’) in front of the building, making a single outdoor reference value for BEL difficult to justify.

Ground-reflected multipath will affect signal values both inside and outside the building. The inside effects are likely to be swamped by multipath from all other reflecting surfaces and in general it is not possible to isolate the effect. We concentrate on determining the effects of ground-reflections on the outdoor reference values.

7.3.1.1 Measurements and models compared

Ground-reflected multipath variations have been investigated using two-ray multipath calculations and measurements made by walking from the Land Rover to the far wall seen in Figure 7-5. This outdoor path was the least obstructed one available in the vicinity of Building B50.2. (The coned off area in the picture was used for signal variability measurements, discussed later).
Figure 7-5: Outdoor path and test area for outdoor variability

The results of the measurement and the 2-ray model prediction are shown in Figure 7-6 and Figure 7-7 for 88 MHz. The walk went out and back, so the far wall occurs halfway through the walk (i.e. at about sample 9000), and was 79m from the Land Rover. Note that the multipath variation depends on the electrical constants of the ground through the Fresnel reflection coefficient. Two ground types are shown, representing likely limits.

Figure 7-6: Measurement data for outdoor path at 88 MHz
Figure 7-7: Model prediction for 88 MHz: very dry ground (blue), wet ground (red)

The 2-ray null near the start (and end) of the walk is predicted by the ground-reflection model (at least for wet ground), but the more rapid variation seen in the measurements must be due to reflected rays with longer delays than come from ground reflections, probably from buildings, trees etc.

The same comparison is made at 5.7 GHz in Figure 7-8 and Figure 7-9.

Figure 7-8: Measurement data for outdoor path at 5.7 GHz
Figure 7-9: Model prediction for 5.7 GHz: very dry ground (blue), wet ground (red)

In this case the model suggests that the more coherent variations seen in the measurement may come from ground reflections, overlaid with rapid variation from buildings, trees etc.

Note that many more multipath peaks and nulls are visible at 5.7 GHz than at 88 MHz. This due to the much longer wavelength at 88 MHz. Indeed at the measurement height used (2m) all 88 MHz measurements are below the lowest interference lobe for distances greater than ~20m.

7.3.1.2 Distance from building

Because these outdoor measurements were affected by distance-dependent variations due to ground-reflected multipath, the question arose as to whether using a single traverse at a fixed, 1m, distance from the front of the building would be adequate as an outdoor reference value. This was tested by making reference measurements at 1, 2 and 3m in front of the building in subsequent measurement runs.

Figure 7-10 shows the 88 MHz reference data runs for Building B50.2 in its foil-backed plasterboard plus metalised windows configuration. The graphs show traverses at 1, 2 and 3m from the front of the building.
Figure 7-10: Outdoor ground-floor reference data at 1, 2 and 3m from the front wall of Building B50.2

As expected at 88 MHz, ‘coherent’ multipath effects are evident, and are indeed different at the three distances. However the median values of each run are 82.0, 84.0 and 82.5 dBμV, respectively. So although the runs look quite different, the median values are within 2dB of each other.

A similar comparison was also made at 5.7 GHz. As expected, the three runs were much less coherent and looked much more similar to each other. The median values of each run are 52.02, 52.01 and 51.99 dBμV, within 0.03dB of each other! This suggests that the differences at 88 MHz may in part be due to undersampling of the multipath across the width of the building—only two or three lobes being seen across each traverse of the house.

We conclude that distance-dependence of multipath fading is not a significant factor affecting our outdoor reference values. In those cases where reference values are available at several distances, the reference value used to calculate BEL was taken to be the average of the individual values.

7.3.1.3 Height gain

The occurrence of ground-reflected multipath effects in these outdoor measurements suggests that the upstairs-downstairs offset seen in the 88 MHz outdoor reference signals (Figure 7-3) could have the same cause.

Predictions have been made of the expected height gain function at the house. Those for 88 MHz are shown in Figure 7-11.
Figure 7-11: Predicted height gain functions at 88 MHz: very dry ground (blue), wet ground (red)

The results are quite sensitive to the ground constants. The results are coherent over the vertical range within which the antenna was moved during either set of measurements, so we would expect to see consistent offsets between the outside downstairs (2m) and upstairs (4.4m) medians. The blue curve shows that the upstairs loss is 3.2dB lower than downstairs loss (i.e. the upstairs signal is higher). This value is lower than the offset seen at 88 MHz in Figure 7-3, but is similar enough to conclude that the upstairs-downstairs difference at 88 MHz is likely to be due to ground-reflected multipath. We cannot claim to predict the actual difference as we don’t have information on the actual ground constants.

The height-gain functions for all five frequencies are shown in Figure 7-12 (for very dry ground).

Figure 7-12: Predicted height gain functions at all measurement frequencies: 88 MHz on right, 5.7 GHz on left

At all frequencies above 88 MHz, there is at least one interference maximum between the downstairs (2m) and upstairs (4.4m) measurement heights. The 217MHz curve (red)
predicts that upstairs loss should be higher than downstairs loss (opposite to 88MHz) which again agrees with the measurements in Figure 7-3. At the higher frequencies the lobing becomes finer grained and slight variations in the antenna height during measurement would be likely to average out any coherent effects.

In conclusion, the modelling has confirmed that the upstairs-downstairs differences seen in the outside reference measurements are likely to be genuine effects caused by ground-reflected multipath. It was therefore decided to use separate reference values for the upstairs and downstairs rooms, rather than taking a single average for the whole house.

### 7.3.2 Path length effects

Unless a transmitter is infinitely distant from a building the signal strengths at the distances of the front and back of the building will be different. This is true even if we ignore the complications due to multipath effects. Even in free space, the $1/d^2$ spread of the radio wave will result in a $20\log(d)$ decrease in signal with distance. The definition of BEL implicitly ignores this effect, and indeed the effect is generally very small in practical applications. However in our experimental setup, the propagation path lengths to the front and back of building B50.2 are approximately 32 and 38m respectively. Assuming free space propagation this amounts to a 1.5dB difference. Therefore, if we use the outside front of the building as the reference point for BEL, inside measurements at the rear of the building would give a value of BEL that would be 1.5dB greater than the value obtained if the propagation path length were much greater. While quite a small effect, we considered correcting the measurement data for it.

The process is not entirely straightforward. One issue is that it may not be valid to assume free space propagation. Indeed we have already shown that ground-reflected multipath is important, and below the first interference lobe this gives a $40\log(d)$ decrease in signal with distance, or 3dB. But because of the very complex mechanisms involved in the propagation of the signal within the building it is essentially impossible to say what distance-dependence to apply in correcting the measurements.

A second difficulty is that we cannot in practice correct every data point individually as we do not record the exact location of each measurement within a room. The best we could do would be to correct the room’s median value which is used for subsequent analysis. In fact the process of extracting the median actually helps to average out the distance-dependent effects within a single room. It also reduces the magnitude of the correction because the relevant path lengths are now the paths to the centroids of each room, rather than to the front and back of the building. Assuming free space propagation, this results in about 0.8dB of signal gradient between front and back rooms, and between the outside reference and the front rooms.

Because of the uncertainties over which path length dependence to assume, we decided not to correct our data values for this effect. Indeed it could be argued that the ‘uncorrected’ building entry losses are actually correct for our propagation path geometry according to the definition of building entry loss. If we were to measure the same building...
using a longer path geometry we would very likely get slightly different building entry losses. However any differences are just as likely to be due to a different multipath environment as to the path length effect.
8 MEASUREMENT - RESULTS

Building entry loss was calculated as the difference between the room medians of received signal level and the relevant outdoor reference field value. In this section we present the measurement results in terms of BEL. The results are presented as a function of frequency on a logarithmic scale to show the trends.

The basic quantities are individual room values of BEL, and these are catalogued first, for each building configuration. This is followed by ‘building-averaged’ results, including front room/back room and upstairs/downstairs comparisons. There is also a discussion of the meaning of ‘variability’ for building entry loss with some results from the new measurements.

Because the main aim of this study is to characterise the impact of modern building materials on building entry loss, we have concentrated on one particular building at BRE (B50.2) which we could reconfigure with different materials. For this building we made measurements in 8 rooms: living room, kitchen and hallway on the ground floor, and 3 bedrooms, bathroom and landing on the upper floor. There were five configurations of this building:

1. The ‘baseline’ house, without any ‘modern’ building materials (labelled ‘Baseline’ on graphs).
2. As in 1, but with secondary double-glazing applied to all windows. The secondary panels included metalised film insulation, although these are about 10 years old and not well characterised (‘Win’).
3. As in 2, but with the addition of foil-backed plasterboard applied to all external walls (‘Win+FBP’).
4. Configuration 3 was repeated using secondary panels of recent low E metalised glazing fitted to all windows. The RF properties of this glass are described in the anechoic chamber measurements of Appendix D (Win2+FBP).
5. As in 3, but in addition all windows were covered in aluminium foil. This is not a practical configuration as it blocks all light from the windows, but was included to estimate the effect that the window apertures were having on the foil-backed insulation (‘Win+Foil+FBP’).

All the above configurations were measured with the receiver vehicle only 10° off the normal to the front of the house. In addition, for one set of measurements (with the house in configuration 4), the vehicle was moved so the path to the vehicle was around 55° degrees from normal (Figure 8-1).
In addition a set of measurements were made in a wing of a larger building at BRE (the Mansion). Measurements were made in 5 rooms and 2 corridors on two floors of the building.

Details of both buildings are given in Appendix C.

8.1 Individual room results

The individual room values of building entry loss are the basic quantities for further analysis.

8.1.1 Baseline

Figure 8-2 shows the results for building B50.2 in its baseline configuration before the fitting of metalised heat insulation products.
The trends are broadly as would be expected, with a monotonic increase in loss between 700 MHz and 5.7 GHz, and with the rooms deeper in the house (kitchen, bathroom, rear bedroom) showing the highest loss.

The behaviour at VHF seems anomalous, with the ground floor rooms (dashed lines) showing unexpectedly high loss at 217 MHz, and losses at 88 MHz higher than might have been expected.

A number of possible explanations for these apparent anomalies suggest themselves, including coherent multipath effects and the fact that the antennas are very close to building surfaces (in terms of wavelength) at these frequencies.

8.1.2 Metalised windows (type 1)

Building 50.2 had been fitted with secondary double glazing some years ago, and the frames in which this had been fitted were still in place. The original glazing units were also located, and these were found to be of metalised glass. Following completion of the ‘baseline’ measurements, the units were fitted to the frames and the series of room measurements repeated.

Figure 8-3 was generated in exactly the same manner as for the ‘baseline’ plot and exhibits the same ‘VHF anomalies’ as before. As the measurements were made on different days, with equipment having been dismantled and re-configured, this makes errors in the test setup a less likely explanation of the anomalies.
Figure 8-3: Building entry loss with metalised windows (type 1)

Comparing these results with Figure 8-2 it can be seen that the impact of the additional windows is small, and this is made more explicit in Figure 8-4, which shows the difference between the ‘windows’ and ‘baseline’ measurements of entry loss; a positive difference implies that the windows are giving additional attenuation.

Figure 8-4: Difference in BEL due to metalised windows (type 1)

The spread of results is smallest at 217 MHz, and suggests that the metalised windows are responsible for some 2dB gain. At the other frequencies the windows give a net loss, although the effect is very small except at 2.4 GHz where it is 1.3dB.
8.1.3 Metalised windows (type 1) and foil-backed plasterboard

After the two previous sets of measurements had been made, building B50.2 was fitted with foil-backed plasterboard on the inner surfaces of all external walls on both floors of the house. Joints were sealed with adhesive aluminium foil strips on the room-facing side of the plasterboard, the foil side of the plasterboard being against the original wall. This is the method by which this material is normally installed.

There were some gaps in coverage, for example under the stairs, and behind radiators, although in the latter case the metal of the radiator would already be highly attenuating to radio waves. In some areas where plumbing pipes prevented plasterboard being attached, aluminium foil was glued to the wall instead. Internal walls, floors and ceilings were left in their original state. Note that the metalised windows were left in place.

Figure 8-5 shows the building entry loss for this configuration. The data still show the upstairs-downstairs anomaly at 217 MHz, although the effect is significantly less for the living room and hallway than in the previous cases. More significantly the entry losses are much larger, except at 5.7 GHz.

![Figure 8-5: Building entry loss with metalised windows (type 1) and foil-backed plasterboard](image)

Figure 8-6 shows the difference between this configuration and the ‘baseline’ measurements of entry loss. At VHF and UHF frequencies the entry loss in all rooms is now clearly greater than that of the baseline configuration, although there is still a large spread between rooms. At 5.7 GHz the attenuating effect of the foil-backed plasterboard appears to be quite small (and in fact becomes slightly negative in three rooms).
8.1.4 Metalised windows (type 2) and foil-backed plasterboard

Because the attenuation of the metalised windows used in the previous two configurations was surprisingly low (Figure 8-4) it was decided to obtain recently manufactured low E glazing and to fit this as secondary panels to the windows of building B50.2 in place of the poorly characterised glazing originally used. Anechoic chamber measurements of this glass (Appendix D) showed that it produces 15–24 dB of attenuation across the measurement frequencies.

Figure 8-7 shows the building entry loss for this configuration. Compared with the corresponding type 1 glass results, Figure 8-5, the losses are generally higher, particularly at the higher frequencies. This is more obvious in the difference between this configuration and the ‘baseline’ measurements of entry loss, Figure 8-8. This shows a generally increasing trend with frequency, except at 5.7 GHz, compared with a flatter frequency dependence for the type 1 glass (Figure 8-6).
Figure 8-7: Building entry loss with metalised windows (type 2) and foil-backed plasterboard

Figure 8-8: Difference in BEL due to metalised windows (type 2) and foil-backed plasterboard

8.1.5 Foil-backed plasterboard and foil over windows

For the final configuration of building B50.2, we decided to investigate the effectiveness of the windows in allowing radio signals to enter the building whose external walls are lined with foil-backed plasterboard.
This was achieved by covering all windows and external doors with aluminium foil in the metalised windows (type 1) and foil-backed plasterboard configured building. The foil was attached across the window apertures to the foil-backed plasterboard walls and gaps sealed with adhesive aluminium foil strips (Figure 8-9). This gave a better seal than could be obtained by attaching the foil directly to the windows as this would also have required covering the window sills and window surrounds.

Figure 8-9: House B50.2 fitted with foil backed plasterboard and foil over windows.

Of course this procedure is not a practical one for normal buildings as it blocks all light from the windows and glazed doors. The measurements are intended to give an idea of the upper limit of attenuation that foil-backed insulation might be expected to achieve in a building of this size.

Figure 8-10 shows the building entry loss for this configuration. The entry loss is larger at the higher frequencies than for the other building configurations, but the situation at the lower frequencies is less clear. The spread of loss between rooms at each frequency is significantly lower than for the other building configurations. The upstairs-downstairs anomaly at 217 MHz is still evident.
Figure 8-10: Building entry loss with foil-backed plasterboard and foil over windows

Figure 8-11 shows the difference between this configuration and the ‘baseline’ measurements of entry loss. Apart from 5.7 GHz the data show increasing loss with frequency which is opposite of what was seen in Figure 8-6 before the windows were sealed with foil!

Figure 8-11: Difference in BEL due to foil-backed plasterboard and foil over windows

For this configuration it is instructive to plot the difference in BEL between this data, Figure 8-10, and the results of Figure 8-5 from before the windows were covered. This graph, Figure 8-12, shows a clear trend to higher attenuation at higher frequencies, with a slope of approximately $10\log(frequency)$. The upstairs rooms at 5.7 GHz are an
exception to the trend. This turnover at 5.7 GHz could perhaps be explained if propagation through the roof begins to dominate at the higher frequencies: the roof-propagated signal would be the same in both configurations. The ‘gain’ produced at 88 MHz by covering the windows in foil is not unphysical, but the mechanism is not obvious.

![Graph showing BEL difference due to covering windows with foil](image)

**Figure 8-12**: Difference in BEL due to covering the windows with aluminium foil, in a house with foil-backed plasterboard insulation.

### 8.1.6 Oblique incidence angle

The results described above were obtained for a path which was close to normal to the front wall of the house. A further set of measurements was made, with the house in ‘configuration 4’ (foil-backed plasterboard and ‘new’ metalised windows’), but with the receiver van positioned at a more oblique angle to the front of the house (see Figure 8-1).
The trend of entry loss seen in Figure 8-13 is now more monotonic with frequency than was the case with any of the configurations measured at near-normal incidence. The difference in entry loss for the two geometries is illustrated in Figure 8-14.

It can be seen that the entry loss has increased for all but the lowest frequency measured. The increase in loss for the two rooms closest to the transmitter at 698 MHz is particularly striking.
8.1.7 The Mansion

The Mansion (or more correctly, one wing of the Mansion) has been included to give some indication of the variation in building entry loss between houses. The Mansion is larger than building B50.2 and has neither metalised windows nor foil-backed plasterboard. It was not possible to ‘reconfigure’ the building as it is in regular use for meeting rooms, so there is only one set of data, shown in Figure 8-15.

Figure 8-15: Building entry loss for the Mansion: dashed lines are ground floor rooms, solid lines are first floor rooms

The mansion shows a fairly uniformly increasing loss with frequency compared to the baseline results for B50.2, Figure 8-2. The losses are generally greater than for the smaller house as would be expected. The inter-room spread is quite large. Interestingly the persistent ‘anomalies’ seen in building B50.2 at 88 and 217 MHz do not occur in the Mansion. This tends to confirm the view that the anomalies are a ‘feature’ of B50.2, possibly caused by multipath effects.

8.2 Building averages

The building entry losses to individual rooms can tell us quite a lot about the distribution and spread of losses within a building. But for modelling purposes, and to help separate ‘the wood from the trees’ it is also useful to consider whole-building values of loss.

In this section we present the results in this aggregated fashion to give a more straightforward quantitative comparison of results. As well as whole building values, some results are given for subsets of the rooms, for example front rooms versus back rooms.

The method used to aggregate room results is simply to calculate the mean value of the individual room medians of interest at each frequency.
Figure 8-16 shows the whole building results for all measured configurations.

The whole building results show most of the features already seen in the single room results:

- Building entry loss generally increases with frequency. For building B50.2, the loss at 88 MHz (and at 217 MHz in two cases) increases for near-normal incidence, which is not easy to explain. The mansion loss shows a fairly uniform logarithmic dependence on frequency across the full range.

- Ignoring the ‘artificial’ foil-over-windows results, the losses are greater than 20dB at 2.4 GHz and reach a maximum of nearly 30dB for 5.7 GHz at oblique incidence to the small house.

- Building entry loss increases as increasing levels of heat insulation material are added for type 1 glass, apart from two cases at VHF, and at 5.7 GHz where the insulation make little difference.

- The level of building entry loss for the type 2 glass and foil-backed plasterboard approaches that of the ‘artificial’ foil-over-windows result, particularly at the higher frequencies.

- Building entry loss is higher for the larger building, except at 88 MHz, than for the baseline (un-insulated) configuration of the smaller building.

- Building loss is higher for the more oblique path to the small house, except at 88 MHz.

Quantitative values for the effect of adding the insulation products is given by the difference between the relevant curve in Figure 8-16 and the baseline configuration (blue line). This is shown in Figure 8-17. (The mansion results relative to the baseline
configuration of B50.2 are included for completeness but of course do not relate to insulation differences.)

![Graph showing BEL comparison](image)

**Figure 8-17: Increase in BEL compared to baseline configuration**

Over the range of our measurements the type 1 metalised windows alone have very little effect. The foil-backed plasterboard adds about 5dB of attenuation at mid frequencies, but this drops to zero at 5.7 GHz. Combining type 2 windows with foil-backed plasterboard gives the highest attenuations at the higher frequencies, reaching 10–15 at 2.4 GHz, depending on incidence angle. The value of 19dB for the oblique measurements at 698 MHz appears anomalous. The artificial foil-over-window excess losses range from 5 to 15dB and may approximate the maximum attenuation attained by insulating a house with foil-backed plasterboard.

It should be noted that both the ‘practical’ configuration of type 2 windows and foil-backed plasterboard, and the ‘artificial’ foil-over-windows configuration result in measured ‘whole-house’ excess attenuations of 10–15dB at 2.4 GHz which is significantly less than the ‘material’ loss of 24dB measured in the anechoic chamber for type 2 glass. This emphasizes the need to base building entry loss figures on in-situ whole-house measurements rather than on the individual material properties.

To help quantify the variation of building entry loss in different parts of a building the back versus front and upstairs versus downstairs differences were calculated for building B50.2. The loss for each subset is given by the mean value of the medians from the relevant rooms. The room plans are given in Annex C. ‘Front’ rooms are living room, hallway, master bedroom (bedroom 2) and front bedroom (bedroom 1); ‘back’ rooms are kitchen, rear bedroom (bedroom 3), bathroom and landing. The living room was, somewhat arbitrarily, included in the front rooms on the basis that it has no internal walls between it and the front wall.
Figure 8-18 confirms that the back rooms experience a higher building entry loss than the front rooms. The magnitude of the differential generally increases with frequency and is ~7dB at 5.7 GHz for type 1 glass, compared to an absolute value of loss of ~20dB, Figure 8-16. However the differential already occurs in the baseline configuration, so the insulation products do not make much difference at any frequency. The artificial foil-over-windows case shows little differential loss over the whole frequency range. This is probably caused by the ‘through-the-front-window’ propagation mode being less dominant in this case. The type 2 glass with foil-backed plasterboard results are intermediate between these two.

![Graph showing building entry loss back-front differences](image)

**Figure 8-18: Building entry loss back-front differences**

Figure 8-19 shows that the upstairs-downstairs differential loss also increases with frequency, apart from the large ‘anomaly’ at 88 MHz. The differential also appears to change sign, with higher losses downstairs at 217 MHz and higher losses upstairs above 698 MHz, but the measured downstairs losses at 217 MHz are problematic (see discussion of Figure 8-2). Type 1 and type 2 glass results are similar. The foil-over-windows value at 5.7 GHz is again exceptional, possibly due to ‘through-the-roof’ propagation.
Variability of building entry loss

Planning models generally make allowance for the variability of building entry loss as well as its average value. The assumption is that there is an underlying statistical distribution of entry loss values, generally characterised by its median and standard deviation values. The shape of the distribution is usually not stated explicitly. However in ITU-R Recommendation P.1812-3 [3.3], building entry loss is combined with location variability (which is lognormal with zero mean) in a way that implicitly assumes the building entry loss to also be lognormal (i.e. normal in decibels, so that the median and the mean have the same value).

The measurement results shown so far can be considered as the median value of building entry loss in such models. Can our measurements provide a figure for the standard deviation?

This answer to this question is not straightforward, because there is no agreed definition of what is meant by the variability of building entry loss. In the open-air, location variability refers to the distribution of loss values, each of which is representative of an area with sides of typically 100m - 500m. Location variability explicitly excludes multipath variations, so the representative values must be obtained by averaging the multipath over each area, leaving only the variability due to shadowing/diffraction. An area of this size is clearly not useful for defining variability on the building scale.

ITU-R Recommendation P.2040 [3.1] does not define building entry loss variability. In fact there is almost no discussion about its statistical properties. Section 4 of P.2040 reports a few building loss measurements. Those which include estimates of standard
deviation all refer to variability within a room. As we have seen, most of this is variability caused by multipath, so this definition of variability does not seem very compatible with the definition of location variability.

An alternative definition of building entry loss variability might be how much the average loss in each room varies from room-to-room. This eliminates the multipath variability, but room-to-room variations will tend to be dominated by the back-front and upstairs-downstairs differentials that we illustrated above. So the magnitude of these variations will depend to a large degree on the size of the building.

A third definition of building entry loss would consider the variation of the whole-building average values of building entry loss across a population of different buildings. This is the definition that is most similar in concept to that of location variability. It would be necessary to define exactly what is meant by a ‘population of different buildings’. Does it mean all buildings of a similar type (e.g. variability within a group of terraced houses), a mixed population of buildings of common usage (e.g. a mix of semi-detached and detached houses on a modern housing estate), or even a population on the scale of a town or even a country (to include domestic, office and industrial buildings)?

With the limited measurements that we have, it is only possible to give results for ‘within room’ and ‘room-to-room’ variability. Although we have results for building B50.2 and the mansion, two buildings are insufficient to say anything about the statistics of variation between buildings.

8.3.1 Within-room variability

In order to understand better the variability of signal level within a room, an area of the same dimensions as the Living Room was marked out outside on a grassed area adjacent to the buildings, Figure 7-5. The distance to this area was the same as to the Living Room.

The measurement data are shown in Figure 8-20 (88 MHz) and Figure 8-21 (5.7 GHz). The same crosshatch pattern was walked both inside and outside, but the inside walk was slower (and hence more data points were collected) due to the need to negotiate furniture in the Living Room.
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 5.5dB (inside) and 1.8dB (outside) and at 5.7 GHz are 6.8dB (inside) and 3.8dB (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.

8.3.2 Room-to-room Variability

The standard deviation of the room median building entry loss values are shown in Figure 8-22 for the different building configurations. There is no very useful frequency trend. The results for the B50.2 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 8-22: Room to room standard deviation of building entry loss](image)

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.

### 8.4 Conclusions

The measurement results serve to illustrate the complexity of the outdoor-indoor propagation path, and the modelling challenge presented by the variability seen within and between buildings.

While it would be unwise to draw general conclusions regarding the statistics of BEL to domestic buildings, the present measurements have provided novel data on the relative impact of a number of energy-efficient building modifications.

- For a small, unmodified house, BEL values around 15-25dB over the range 88 MHz – 5.8 GHz were seen in the room farthest from the outdoor terminal. The lowest losses seen were around 5dB at VHF and UHF frequencies. The spread in loss values between rooms seemed anomalously large at 217 MHz.
- Surprisingly high losses were seen at VHF frequencies for near-normal orientation in small house, but these results were not seen at oblique angle or in the larger ‘mansion’
- Adding foil-backed plasterboard (FBP) and an older set of metalised windows increased losses by some 5dB, although the impact was minimal at the highest
frequency. The increased loss due to the use of FBP was greatest in the upstairs rooms.

- With FBP and a set of newly manufactured low-E windows, the additional loss was greater, except at 217 MHz. The variation in the additional loss seen to different rooms was considerable, at around 10dB.

- With walls completely lined with foil (i.e. FBP and foil over the window apertures) the maximum losses were increased somewhat, but the greatest impact was that the spread of the additional loss seen between rooms is significantly reduced. Surprisingly the addition of the foil over the window apertures caused the losses seen at 88 MHz to decrease.

- When the incidence angle of the path into the house was changed, the trend of loss with frequency became rather more monotonic, with losses being greater than the near-normal case at all frequencies except 88 MHz; The ‘anomalous’ behaviour seen at 217 MHz was no longer evident.

- Building entry loss is higher for the larger building, except at 88 MHz, than for the baseline (un-insulated) configuration of the smaller building.

As might be expected, it was found that received signal variability was significantly greater inside the building than outside, the difference being largely due to additional multipath fading. It is noted that the definition of terms relating to signal variability on indoor paths requires clarification.

To obtain reliable statistics with which to characterise entry loss into UK domestic buildings in general will require further measurement.

Useful additional insight into the mechanisms involved in determining building entry loss might be obtained by attempting to replicate some of the behaviour seen in the present measurements using ray-tracing, or other modelling methods.
## Glossary

### AD
Approved Document (Building Regulations). Part L concerns energy efficiency

### BBA
British Board of Agrément (certification of construction products and practices)

### Brewster angle
The angle of incidence at which minimum reflection occurs from a boundary between two media

### CERT
Carbon Emissions Reduction Target

### CW
Continuous Wave (i.e. an unmodulated radio transmission)

### CWI
cavity wall insulation

### CWISC
cavity wall insulation Self Certification Scheme

### CESP
Community Energy Saving Programme

### DCLG
Department for Communities and Local Government

### DECC
Department of Energy & Climate Change

### ECO
Energy Company Obligation

### EEC
Energy Efficiency Commitment (1 & 2)

### EHS
English Housing Survey

### GD
Green Deal (Government energy efficiency initiative)

### GD ORB
Green Deal Oversight and Registration Body

### Permeability (μ)
Describes impact of a material on a magnetic field

### Permittivity (ε)
Describes impact of a material on an electric field

### SD
Standard Deviation

### SWI
solid wall insulation

### SWIGA
Solid Wall Insulation Guarantee Association

### U-value
Overall heat transfer coefficient or thermal transmittance (W/m²K)

### VNA
Vector Network Analyser
B    BIBLIOGRAPHIES & REFERENCES

B.1 Building materials


[1.4] AIMC4 project. The project website can be found at: http://www.aimc4.com/index.jsp


B.2 Material properties

[2.1] “Effects of building materials and structures on radiowave propagation above about 100 MHz”, ITU-R Recommendation P.2040, September 2013, available at uct


B.3 Effect of Buildings on propagation


C Measurement Locations

C.1 Building 50.2

The majority of the measurements took place at building B50.2, which is the second building from the left in Figure C-1 below.

Figure C-1: B50 test houses at BRE

B50.2 is built to the UK Building Regulations (1995) and has levels of insulation to just beyond the 1995 Part L requirements. It has a filled cavity construction (brick/block) and single glazed windows enhanced with secondary glazing.

For the measurements, the Land Rover carrying the receive antennas was positioned 32m from the front of the house, as shown in Figure C-2.

In the figures below, room dimension are between walls. Internal walls are about 100mm thick while external walls are about 300mm thick (100mm brick, 100mm cavity, 100mm block).
Figure C-2: Relative location of receive antennas

Ground Floor

- Radiator
- Window

Figure C-3: Ground floor plan
C.1.1 Internal photographs

The following figures show the interior arrangement of House 50.2.

Figure C-4: First floor plan

Figure C-5: Living room (to front window)
Figure C-6: Living room (to rear window)

Figure C-7: Kitchen
Figure C-8: Hallway

Figure C-9: Main front bedroom (bedroom 2)
Figure C-10: Small front bedroom (bedroom 1)

Figure C-11: Rear bedroom

Figure C-12: Bathroom
C.2 Mansion

One wing of this large Victorian house was used for comparative measurements. The relevant part of the building and the location of the receiver vehicle are shown below.

Figure C-13: Mansion and location of receive antennas

The view from the back of the mansion is shown in Figure C.14, with individual room locations indicated.
C.2.1 Internal photographs

The following figures show the interior arrangement of the rooms used for the measurements.
Figure C-16: Room 101

Figure C-17: Room 102
Figure C-18: Room 103

Figure C-19: Looking from Room 101 towards upstairs corridor
Figure C-20: Downstairs corridor

Figure C.21: Room 003/004
Figure C.22: Room 002
D ANECHOIC CHAMBER MEASUREMENTS

D.1 Methodology

The measurements were made in the anechoic chamber at BRE. The anechoic chamber has double doors which open to allow equipment to be moved in and out of the chamber. The building containing the anechoic chamber has a large retractable door opposite the chamber double doors to help with movement of equipment in and out of the building. For these tests, the chamber doors were left open and the test samples were fitted inside the door frame.

The building retractable door was left open and the transmit antenna was placed outside the chamber, 3m from the test sample. The receive antenna was placed inside the chamber also at a distance of 3m from the test sample. Both antennas were aligned with the centre of the sample.

Radar absorbent material (RAM) was placed on the ground between each antenna and the sample to reduce the effect of any ground reflections on the results. Figure D-1 shows the transmit antenna outside the chamber with the RAM on the ground between the antenna and the test sample.

Figure D-1: The transmit antenna outside the chamber, receive antenna inside the chamber and RAM on the ground between the antennas and the sample location in the doorway opening.
The measurements were made using log-periodic and Bilog antennas for transmit and receive for the frequencies 88MHz, 217 MHz and 698MHz. For the frequencies 2410MHz and 5760MHz, a double-ridge waveguide horn antenna was used as the receive antenna and a shrouded log-periodic was used as the transmit antenna.

A CW signal was transmitted at each frequency for both horizontal and vertical polarisations and received on a spectrum analyser in an ante-chamber.

D.2 Samples

Each sample was 201cm (H) x 210cm (W) and foil tape was used to join the samples to anechoic chamber door frame. The samples tested were:

- Foil backed plasterboard
- Low E glazing
- Foil-backed insulation board – 100 mm thick with foil on both sides – typically used for cavity wall insulation and roof insulation.

The dimensions of the 50mm thick foil backed insulation board purchased was 1.2m by 2.4m. Two samples were cut to be 2.01m by 1.05m and were fitted with the large dimension across the width of the door, with the gap across the centre foil taped, as shown in Figure D-2. The sample was then foil taped to the metal door frame of the chamber.

Figure D-2: The 50mm thick foil-backed insulation board sample.
For practical reasons, the metallised glass was purchased as four separate panels and two panels were constructed into an upper wooden frame and two into a lower wooden frame, Figure D-3. When installed, the sample was foil taped along the horizontal and vertical centre lines shown in Figure D-3.

![Figure D-3: Construction of the metallised glass sample.](image)

Two completed sample was installed inside the chamber door opening and the edges were then foil taped to the metal door frame of the chamber, D-4.
Figure D-4: The metallised glass sample fitted inside the chamber door opening, looking into the chamber from the transmit antenna location.

The foil-backed plasterboard was constructed in upper and lower wooden frames in the same way as for the metallised glass sample, with foil tape placed around the edges of the frames which overlapped the foil face of the plasterboard. The installed sample, Figure D-5, was then foil taped across the horizontal centre and the foil taped to the door opening around its edges.
D.3 Results

Measurements were made with each sample, for the antennas in the horizontal and vertical polarisation. Reference measurements were made with no test sample in the chamber door opening. The measurements with each sample were compared with the reference measurements and the results are shown in Figure D-6. The results show that the metallised glass sample produced about 20 to 25dB of loss, the foil-backed plasterboard about 35 to 45 dB of loss and the 50mm foil-backed insulation board about 50 to 60dB of loss. The 50mm foil-backed insulation board has foil on both faces.

There vertical polarisation results were generally lower than the horizontal polarisation results. It is thought that this must be due to either the structure of the sample, or more likely the measurement environment, although there was not sufficient time to explore this.
Figure D-6: Measurement results showing the shielding effectiveness of each sample for both horizontal and vertical polarisations.

The losses for each sample and frequency were averaged over the measurement results for the horizontal and vertical polarisations and the average losses are shown in Table D-1.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Insulation board</th>
<th>Plasterboard</th>
<th>Glass</th>
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<tr>
<td>88.4</td>
<td>48</td>
<td>46</td>
<td>22</td>
</tr>
<tr>
<td>217</td>
<td>61</td>
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<td>32</td>
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<td>54</td>
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</tr>
<tr>
<td>5760</td>
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<td>38</td>
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