COMPARISON OF RADIO PROPAGATION CHARACTERISTICS AT 700 AND 2,500 MHz PERTAINING TO MACROCELLULAR COVERAGE

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Executive Summary

Frequency-dependent features of signal transmission performance in several radio propagation environments characteristic of macrocellular radio networks are evaluated. Frequency bands of specific interest are 700 MHz and 2,500 MHz (2.5 GHz). The objective of the study is to analyze technical aspects of propagation behaviour in cluttered environments, in order to permit general observations regarding the relative merits of these frequency bands with respect to area coverage. The CRC-Predict propagation prediction algorithm [1], well-validated and widely licensed for system coverage design, was employed for the calculations.

To achieve some general technical validity of conclusions derived from the study, a varied set of representative base station locations and signal transmit heights was selected, based on reference to the Industry Canada Assignment and Licensing System (ALS) database. The locations were selected with the intention to demonstrate the progression of propagation characteristics in environments from open rural to heavily foliated and urban/suburban, including influence of significant terrain variations.

Results for these environments are provided in Table 2 and Appendix A, in the form of path loss differences, as well as ratios of overall area covered at 700 and 2,500 MHz as a function of path loss. Coverage plots corresponding to the two frequencies are also provided. These results correspond solely to the attenuation, due to wave interaction with the propagation environment, of a signal launched by any means at a specified base station antenna height and received at multiple receive locations with a specified mobile station antenna height. While system configuration (other than antenna heights) and system parameters (transmit power, antenna characteristics, etc.) play a critical role in the performance of any telecommunication system, they are not dealt with in the main analysis. However, a review of other factors that may influence system design differently at the two frequencies of interest is provided in Appendix B.

Based on the results presented in the remainder of this report, the following general technical observations are made:

- For the five propagation scenarios investigated in this study, representative of rural as well as urban/suburban environments, the mean path loss advantage at 700 MHz versus 2,500 MHz ranges approximately from 11–14 dB, except for hilly forested terrain, where the difference is about 18 dB (Table 2).

- As illustrated by the coverage plots in Appendix A (e.g., Fig. A.1), the lower path loss at 700 MHz offers the potential for increased coverage area per base station, assuming that link budgets for the two frequencies allow for identical maximum path loss values. If issues related to network capacity are left out of consideration, the number of base stations required to provide wireless service in a given area is roughly inversely proportional to the area covered by a single base station. This implies that, under the aforementioned conditions, fewer base stations would be required at 700 MHz than at 2,500 MHz.

- The advantage of 700 MHz versus 2,500 MHz in terms of area covered can be quantified as follows. For relatively low path loss values, corresponding to relatively small cell radii,
the coverage area at 700 MHz is found to be roughly an order of magnitude larger than at 2,500 MHz. However, the results in Appendix A show a consistent tendency for the ratio of coverage areas at 700 MHz versus 2,500 MHz to diminish as path loss increases, typically to ratios of 2–3 for path loss values corresponding to large cell radii. To preserve the coverage area advantage associated with 700 MHz for large path loss values, it may be necessary to employ greater base station antenna heights, as discussed in the Analysis and Results section.

- The preceding observations are based on path loss calculations for mobile station locations outside any buildings, and do not take into account signal losses due to wave penetration into buildings. Based on empirical results (Table 5), average building penetration losses in residential areas are estimated to be 3.9 dB lower at 700 MHz than at 2,500 MHz; as a result, indoor coverage near cell boundaries in such environments is expected to be comparatively better at 700 MHz. In industrial/commercial environments, on the other hand, average building penetration losses are estimated to be 4.3 dB higher at 700 MHz, leading to decreased indoor coverage performance with respect to 2,500 MHz.
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Analysis and Results

Propagation Model

There are widespread conventional perceptions related to the utility of the 700-MHz frequency band for macrocellular wireless coverage, as compared to higher-frequency regions such as the 2,500-MHz band. For a scientifically-based evaluation of such perceptions, a propagation model is required which provides accurate path loss estimates for propagation scenarios relevant to macrocellular radio networks operating at the aforementioned frequencies.

A broad assortment of prediction methods are available for coverage estimation, but most are not valid over the range of frequencies and distances necessary to be considered for the analysis herein. In addition, most are empirically derived and cannot reflect the details of a specific environment, except in a statistical sense based on general environmental categories. To correlate predicted coverage capabilities with physical propagation processes, a physically-based propagation model is used for all predictions in this study. In particular, the CRC-Predict prediction algorithm [1], well-validated and widely licensed for system coverage design, was employed for the calculations.

CRC-Predict relies on physical optics (Fresnel-Kirchhoff theory) algorithms to perform path loss estimation, accounting for detailed terrain elevations with general land-cover categories, and performs best when the base station antenna is above local clutter (as here). It accounts for diffraction due to environmental clutter along defined radials from the base station as well as additional local losses due to buildings and vegetation near the receiver location [1]. Due to its physically-based nature, prediction errors associated with CRC-Predict are generally smaller than those of empirically-based methods; as well, the general nature and magnitudes of the errors should be similar at the two frequencies due to the fact that all rely on simulation of the same propagation mechanisms in the same environments.

Site Selection

In order to be able to analyze coverage performance under approximately realistic conditions, position and height parameters corresponding to five actual base station sites were selected from Industry Canada’s Assignment and Licensing System (ALS) database, which is accessible through the Spectrum Direct on-line service [2]. The five sites selected, which are shown in Fig. 1 and relevant parameters of which are listed in Table 1, correspond to Bell Mobility-operated transmitter stations within a 50-km radius from downtown Ottawa. Each represents a different type of propagation environment relevant to macrocellular radio networks; three sites are in rural areas of different terrain and land cover types, one is located in a suburban area, and one in a medium-density urban area. These locations were selected to demonstrate progression from open rural to heavily foliated and (sub)urban environments, including the influence of significant terrain variations.

Data Generation and Processing

With the aid of the CRC-COVLAB software [3], path loss calculations based on the CRC-Predict algorithm were performed for rectangular grids of mobile station locations in areas around each of
Table 1: Base station sites selected for coverage calculations.

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Address</th>
<th>Position</th>
<th>Antenna Height (m)</th>
<th>Environment Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lot 6, Concession 3, Route 400, Russell, ON</td>
<td>45°14'41&quot;N 75°18'55&quot;W</td>
<td>91</td>
<td>Open Rural</td>
</tr>
<tr>
<td>2</td>
<td>5001 Dwyer Hill Rd, Ottawa, ON</td>
<td>45°05'57&quot;N 75°54'43&quot;W</td>
<td>100</td>
<td>Forested Rural</td>
</tr>
<tr>
<td>3</td>
<td>165 Chemin du Fort, Val-des-Monts, QC</td>
<td>45°40'53&quot;N 75°44'53&quot;W</td>
<td>90</td>
<td>Hilly Forested Rural</td>
</tr>
<tr>
<td>4</td>
<td>1075A Greenbank Rd, Ottawa, ON</td>
<td>45°16'34&quot;N 75°44'55&quot;W</td>
<td>48</td>
<td>Suburban</td>
</tr>
<tr>
<td>5</td>
<td>1575 Carling Ave., Ottawa, ON</td>
<td>45°22'52&quot;N 75°44'46&quot;W</td>
<td>48</td>
<td>Urban</td>
</tr>
</tbody>
</table>

Fig. 1: Base station sites selected for coverage calculations.
the selected sites. At each point in the grid, a path loss value was computed using a 30-m-resolution terrain elevation database called CDED (Canadian Digital Elevation Data) and a 100-m-resolution land cover database, both of which are available from the GeoBase website [4]. In all calculations, the distance between adjacent grid points (resolution) was chosen to be 100 m, the mobile station antenna height was set to 1.5 m above local ground level, and effects of antenna characteristics were left out of consideration. A large sample of path loss difference values corresponding to the two frequencies considered was obtained by subtracting predicted path loss values at 700 MHz from corresponding path loss values at 2,500 MHz.

In order to evaluate the implications of path loss differences between the two frequencies with respect to coverage area, coverage contours were determined for path loss values in the range from 100 to 160 dB; corresponding coverage area figures were then calculated by counting the number of grid points within each contour. Contour plots and plots of area covered as a function of path loss are provided in Appendix A. Results based on the ITU-R Recommendation P.1546 empirical path loss model and the free-space path loss model, which, unlike CRC-Predict, do not take into account specific details of each propagation environment, are shown for comparison.

**Interpretation of Results**

Analysis of the path loss data obtained according to the aforementioned method shows that, for each of the five environments considered, the path loss difference between 700 and 2,500 MHz has an approximately lognormal distribution. The mean and standard deviation of these distributions vary somewhat with the radius around the base station within which path loss difference statistics are calculated; both tend to increase slightly with increasing cell radius. Values corresponding to a cell radius of 30 km, often quoted (without reference) as the upper limit for rural macrocells, are provided in Table 2. The mean path loss difference is seen to be approximately in the range from 11 to 14 dB, except for the environment representative of hilly terrain, for which the mean path loss difference is approximately 18 dB. The standard deviation is 5–6 dB. These values are in good general agreement with observations made in [5] regarding rural and urban/suburban (non-hilly) environments, which lead to the conclusion that the path loss increase at 2,500 MHz compared to 700 MHz is 11–15 dB (also refer to Section B.1.3 in Appendix B). The higher mean path loss

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Environment Type</th>
<th>Mean (dB)</th>
<th>Standard Deviation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Open Rural</td>
<td>10.8</td>
<td>6.1</td>
</tr>
<tr>
<td>2</td>
<td>Forested Rural</td>
<td>11.3</td>
<td>5.0</td>
</tr>
<tr>
<td>3</td>
<td>Hilly Forested Rural</td>
<td>18.4</td>
<td>5.8</td>
</tr>
<tr>
<td>4</td>
<td>Suburban</td>
<td>11.9</td>
<td>5.6</td>
</tr>
<tr>
<td>5</td>
<td>Urban</td>
<td>14.3</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Table 2: Mean and standard deviation of path loss difference between 2,500 MHz and 700 MHz.
difference observed for hilly terrain is explained by the fact that the overall propagation loss in this type of environment is dominated by diffraction attenuation due to terrain obstacles, which is well-known to be more severe at higher frequencies.

The CRC-Predict area coverage results provided in Appendix A show that the ratio of area covered at 700 MHz versus that at 2,500 MHz can vary considerably as a function of the path loss contour value. (Be aware that small deviations in the coverage calculations at either, or both, frequencies can be reflected as more pronounced changes in the ratio of coverage areas.) For the lowest values of path loss shown on the plots, the advantage of 700 MHz over 2,500 MHz is similar to what might be expected based on distance and frequency-dependence relations associated with free-space propagation: the ratio of coverage areas at 700 MHz versus 2,500 MHz is approximately equal to the inverse squared ratio of the two frequencies (refer to Sections B.1.2 and B.1.3 in Appendix B).

There is a tendency for the ratio of coverage areas computed by CRC-Predict to decrease noticeably as the path loss increases. For the Open Rural environment (Figs. A.1–A.3), for example, the coverage-area ratio first oscillates around the free-space value, then decreases to about two for a path loss of 130 dB, and maintains that general value as path loss continues to increase. The same tendency manifests itself in the plots for the other representative environments, although not quite identically. A similar trend is observed in the curves corresponding to the ITU-R Recommendation P.1546 empirical model, even though the coverage area predicted by this model is usually smaller than that of CRC-Predict at both frequencies, and the coverage-area ratio is usually larger (illustrating advantages obtained by applying environment-specific procedures in preference to average empirical predictions).

A possible explanation for the diminishing advantage of 700 MHz over 2,500 MHz with increasing path loss is that, for identical antenna heights at the two frequencies, as is assumed in this analysis, the probability of Fresnel zone blockage at 700 MHz is greater than that at 2,500 MHz, which may be significant for longer paths and correspondingly greater path loss. The radius of the first Fresnel zone is inversely proportional to the square root of the frequency; consequently, the Fresnel zone radius at 700 MHz is nearly twice that at 2,500 MHz. To achieve a similar degree of Fresnel zone clearance at 700 MHz as at 2,500 MHz, it may be necessary to employ greater base station antenna heights. This factor, along with other system configuration issues, may be addressed in system design, not considered here.

Relation to Previous Results

Some discussion of results presented herein may be warranted in the context of apparent common perceptions that propagation advantages in terms of coverage area at 700 MHz are distinctly superior to those at 2,500 MHz. There are definite advantages as illustrated by the results presented herein. However, the advantages sometimes quoted appear to be based on empirically-based analyses whose validity might be questioned.

For example, estimates of cell radius at 700 MHz and 2,500 MHz presented in Reference [6] indicate a ratio that increases to relatively large values as path loss increases, somewhat contrary to the ratios derived herein. The analysis in [6] uses the Okumura-Hata model at 700 MHz and
a frequency-scaled version of the COST 231-Hata model at 2,500 MHz (refer to Section B.1.4 in Appendix B). Both Okumura-Hata and COST 231-Hata are simple one-slope methods with a constant increase in predicted loss with respect to increasing path length, with constant path loss adjustments depending on the environment category. The frequency dependence of these two models changes rather sharply at 1,500 MHz from $26.16 \cdot \log_{10} f$ to $33.9 \cdot \log_{10} f$, respectively. Extension of the COST 231-Hata model beyond its normal upper frequency of 2 GHz involves another frequency-scaling factor of $26 \cdot \log_{10}(f/2)$, with the frequency specified in GHz. These adjustments in frequency give the appearance of possibly exaggerating the path loss at 2,500 MHz in comparison with the loss at 700 MHz. Application of a model using the same calculation algorithm that is recommended for the full frequency range, such as CRC-Predict or ITU-R P.1546, seems better founded.
References


Appendix A
Coverage Prediction Results
A.1 Site #1: Open Rural

Fig. A.1: Coverage plots for site #1 (Open Rural), at (a) 700 MHz and (b) 2,500 MHz.
Fig. A.2: Coverage area at 700 and 2,500 MHz versus path loss for site #1 (Open Rural).

Fig. A.3: Ratio between coverage areas at 700 and 2,500 MHz versus path loss for site #1 (Open Rural).
A.2 Site #2: Forested Rural

Fig. A.4: Coverage plots for site #2 (Forested Rural), at (a) 700 MHz and (b) 2,500 MHz.
Fig. A.5: Coverage area at 700 and 2,500 MHz versus path loss for site #2 (Forested Rural).

Fig. A.6: Ratio between coverage areas at 700 and 2,500 MHz versus path loss for site #2 (Forested Rural).
A.3 Site #3: Hilly Forested Rural

Fig. A.7: Coverage plots for site #3 (Hilly Forested Rural), at (a) 700 MHz and (b) 2,500 MHz.
Fig. A.8: Coverage area at 700 and 2,500 MHz versus path loss for site #3 (Hilly Forested Rural).

Fig. A.9: Ratio between coverage areas at 700 and 2,500 MHz versus path loss for site #3 (Hilly Forested Rural).
A.4 Site #4: Suburban

Fig. A.10: Coverage plots for site #4 (Suburban), at (a) 700 MHz and (b) 2,500 MHz.
Fig. A.11: Coverage area at 700 and 2,500 MHz versus path loss for site #4 (Suburban).

Fig. A.12: Ratio between coverage areas at 700 and 2,500 MHz versus path loss for site #4 (Suburban).
A.5 Site #5: Urban

Fig. A.13: Coverage plots for site #5 (Urban), at (a) 700 MHz and (b) 2,500 MHz.
Fig. A.14: Coverage area at 700 and 2,500 MHz versus path loss for site #5 (Urban).

Fig. A.15: Ratio between coverage areas at 700 and 2,500 MHz versus path loss for site #5 (Urban).
Appendix B

Review of Frequency-Dependent Link Budget Items

B.1 Path Loss

B.1.1 Definition

In land-mobile communications, the term path loss generally means the sum of all losses experienced by a radio signal along its propagation path, excluding the effects of antenna gain and fast fading due to multipath propagation [7]. In mobile scenarios, path loss usually applies to the signal attenuation exceeded for 50% of time or for 50% of locations at a given distance from the base station, or within a small area in the vicinity of the mobile station (median path loss), assuming the antennas to be isotropic. In this appendix, the symbol $L$ represents median path loss expressed in decibels (dB).

B.1.2 Dependence on Distance

As radio signals propagate out from the base station antenna, their intensity decreases with distance, $d$. The simplest useful prediction model for this distance-dependence is a power-law model of the form [8]

$$L = 10n_d \cdot \log_{10}(d/d_0) + L_0;$$  \hspace{1cm} (B.1)

where $L_0$ is the predicted path loss at a reference distance $d_0$, and $n_d$ is the so-called path loss exponent. Because the area covered by a base station increases as the square of its range—the maximum distance at which $L$ is below some system-dependent threshold—the path loss exponent is critical in establishing the coverage of a cellular system.

It is well-understood that the above power-law model is exact, with $n_d = 2$, for free-space propagation, a hypothetical propagation condition in which there is no obstruction of the wireless signal by terrain, buildings or other natural or man-made objects. In more realistic scenarios, $n_d$ has been found by measurement to depend on various parameters, including antenna heights, terrain elevation and land cover; it is greater than 2 except in certain anomalous propagation conditions such as ducting and canyoning, which are rare in macrocellular systems operating in the UHF frequency range. As a general rule, the path loss exponent increases with decreasing antenna height and at large distances from the base station, where (partial) obstruction of the first Fresnel zone becomes more likely. It also increases for hilly and mountainous terrain, and for land cover types associated with a high density of obstructions in the signal path (e.g., forested and/or built-up areas). As a result of the observations above, total path loss is often considered to be the sum of the free-space path loss and the so-called excess path loss, of which the path loss exponent is $n_d - 2$.

B.1.3 Dependence on Frequency

Free-space path loss is proportional to the square of frequency because the effective receiving area, or aperture, of a nondirectional antenna is proportional to the square of the wavelength. The
excess path loss also increases with frequency, although more weakly than the free-space path loss, because of the larger diffraction losses at shorter wavelengths. Thus, in a first-order approximation, the path loss at frequencies \( f_1 \) and \( f_2 \) is related as

\[
L_{f_2} = L_{f_1} + \Delta L(f_2, f_1),
\]

where

\[
\Delta L(f_2, f_1) = 10n_f \cdot \log_{10}(f_2/f_1).
\]

It has been found [5] that \( n_f \) is approximately 2.6 for urban and suburban areas, and close to 2.0 for open rural areas, where diffraction losses are much less significant. According to this approximation, the median propagation loss in the 700 MHz spectrum band is expected to be 11 dB lower in the 700-MHz band than in the 2,500-MHz band for open rural areas, and 15 dB lower for urban and suburban areas.

### B.1.4 Models

To plan and optimize cellular radio networks, accurate path loss models, often also referred to as propagation models, are required. Two broad categories of propagation models are available: empirical models and physically-based models.

Empirical path loss models are widely used for the planning and optimization of cellular networks. They treat the path loss associated with a given macrocell as dependent on distance, provided that the environment surrounding the base station is flat and fairly uniform. In consequence, the coverage area predicted by these models for an isolated base station will be approximated as circular; although this is clearly inaccurate, it is useful for system dimensioning purposes [8].

Empirical models are created by fitting appropriate mathematical functions to extensive sets of measured path loss data; no attempt is usually made to base these functions on physical models of dominant propagation mechanisms. Correction terms and factors are often derived for particular propagation environments, frequencies and antenna heights, such that the error between the model and the measurements is minimized. A common categorization of propagation environments is [8]

- **Open area**: open space, no tall trees or buildings in path, plot of land cleared for 300–400 m ahead, e.g., farmland, rice fields, open fields.
- **Suburban area**: village or highway scattered with trees and houses, some obstacles near the mobile but not very congested.
- **Urban area**: built-up city or large town with large buildings and houses with two or more storeys, or larger villages with close houses and tall, thickly grown trees.

The resulting models can then be used to design systems operated in similar environments to the original measurements. While they are computationally efficient, empirical models are often not very accurate since they do not explicitly account for specific propagation phenomena.

Physically-based propagation models, on the other hand, are typically more accurate but require more information regarding the type of environment and terrain in the area around the base station. They attempt to model the actual wave interaction with the environment, and typically rely on physical models of reflection, diffraction, and/or scattering.
**Okumura-Hata**

The Okumura-Hata model [9] is probably the single most common model used in designing real-world systems [8]. It is an empirical model based on measurements performed in and around Tokyo in the 1960s [10]. As shown in Table 3, the Okumura-Hata model’s validity range is fairly limited, and does not fully cover the frequencies and range values of interest in the present study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Min. Value</th>
<th>Max. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>MHz</td>
<td>150</td>
<td>1,500</td>
</tr>
<tr>
<td>BS Antenna Height</td>
<td>m</td>
<td>30</td>
<td>200</td>
</tr>
<tr>
<td>MS Antenna Height</td>
<td>m</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Range</td>
<td>km</td>
<td>1</td>
<td>20</td>
</tr>
</tbody>
</table>

**COST 231-Hata**

As a result of research activities in COST 231, the Okumura-Hata model has been extended to cover frequencies up to 2,000 MHz [11]. The resulting COST 231-Hata model was developed specifically for urban and suburban macrocells; its applicability to rural areas has not been clearly established.

**Frequency-Scaled COST 231-Hata**

In a 2008 study comparing WiMAX deployment at 700 MHz and 2,500 MHz [6], the COST 231-Hata model was extended to cover the 2,500-MHz frequency band by applying a frequency scaling factor of the form defined in Eq. (B.3) to the COST 231-Hata model. It was reported that this method provides acceptable results for frequencies up to 6 GHz, but little or no scientific support for this claim appears to be available.

**ITU-R P.1546**

ITU-R Recommendation P.1546 [12] describes a step-by-step method for predicting path loss in point-to-area terrestrial radio links in the frequency range from 30 to 3,000 MHz. The method is based on interpolation/extrapolation from empirically derived field-strength curves as functions of distance, antenna height, frequency and percentage time. The calculation procedure also includes corrections to the results obtained from this interpolation/extrapolation to account for terrain clearance and terminal clutter obstructions. The model has been reported to produce similar results to the Okumura-Hata method for distances up to 10 km, a mobile station antenna height of 1.5 m and a clutter height around the receiver of 15 m [12]. However, as shown in Table 4, it is valid over
a much wider range of parameter values than Okumura-Hata, and fully covers the frequencies and range values considered in the present study.

Table 4: Validity range of the ITU-R P.1546 path loss model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Min. Value</th>
<th>Max. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>MHz</td>
<td>30</td>
<td>3,000</td>
</tr>
<tr>
<td>BS Antenna Height</td>
<td>m</td>
<td>30</td>
<td>3,000</td>
</tr>
<tr>
<td>MS Antenna Height</td>
<td>m</td>
<td>1</td>
<td>3,000</td>
</tr>
<tr>
<td>Range</td>
<td>km</td>
<td>1</td>
<td>1,000</td>
</tr>
</tbody>
</table>

CRC-Predict

CRC-Predict is a physically-based path loss prediction model developed at the Communications Research Centre Canada [1]. The main calculation performed by the model is that of diffraction attenuation due to terrain obstacles, based on machine-readable topographic databases consisting of elevation data. These obstacles are primarily hills, or the curvature of the earth, but can also include trees and/or buildings. The diffraction calculation is done by starting at the transmitting antenna and finding the radio field at progressively greater distances. At each step, the field at a point is found by a numerical integration over the field values found in the previous step. For long paths, tropospheric scatter becomes important. CRC-Predict combines the tropospheric scatter signal with the diffraction signal.

B.2 Other Frequency-Dependent Factors

B.2.1 Building Penetration

Apparently conflicting results have been reported in the literature concerning the dependence of building penetration loss on frequency [13–15]. While several researchers have reported measurements indicating that building penetration loss decreases with increasing frequency in the VHF and UHF range [14], results by other researchers suggest the opposite, for example see [13, 16–18], or that there is no significant dependence on frequency at all [11].

It has been noted [13, 14] that the frequency dependence of penetration loss appears to be strongly dependent on the type of building construction. For residential buildings, which are typically constructed from non-metallic building materials such as wood, cinder block, brick veneer and glass, penetration loss has been found to be relatively low and to increase with increasing frequency. This observation is supported by results of laboratory measurements on a variety of common building materials, reported in [19], which show that, while propagation losses through most building materials are almost the same at 2.4 and 5 GHz, red brick and cinder block are notable exceptions; losses associated with these materials are 10.1 and 3.6 dB higher, respectively, at the higher frequency. Industrial and commercial buildings, on the other hand, are often
of steel-framed construction, and the corresponding predominant building materials are reinforced concrete, steel, and aluminum; loss through these materials is relatively much higher, and the dominant penetration mode is through slots such as windows and other frame openings, or even through grid openings in steel-reinforced concrete slabs. Losses associated with propagation through slots tend to be strongly frequency-selective, and overall decrease with increasing frequency, as the slot dimensions become larger in terms of the wavelength.

Davidson and Hill [14] collected and analyzed measured data from various research groups and reported that penetration loss values associated with industrial or commercial buildings can be fitted reasonably well to a -7.9-dB/decade regression line. Using the same procedure on the residential building data reported in [13, 16], a +7.2-dB/decade regression line is obtained, as shown in Fig. B.1. Estimates of building penetration loss values at 700 and 2,500 MHz derived from these regression lines are provided in Table 5. The estimates for residential buildings are considered to be of greater relevance to the application considered in this report, as this type of building is more likely to be located near macrocell boundaries.

<table>
<thead>
<tr>
<th>Building Type</th>
<th>700 MHz</th>
<th>2,500 MHz</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>4.6</td>
<td>8.5</td>
<td>[13, 16]</td>
</tr>
<tr>
<td>Industrial/Commercial</td>
<td>14.5</td>
<td>10.2</td>
<td>[14]</td>
</tr>
</tbody>
</table>

Fig. B.1: Measured building penetration loss versus frequency, for residential buildings.

Table 5: Estimates of building penetration loss, in dB, at 700 and 2,500 MHz.
B.2.2 Shadowing

Shadow fading is the difference between the actual, locally observed path loss and the median path loss predicted by a path loss model, and is a result of particular obstructions in the propagation path (buildings, trees, etc.) [8]. Its probability distribution has consistently been found to be log-normal [20], i.e., the fading loss in dB has a normal distribution. To provide reliable coverage, a fading margin has to be added to the link budget according to the reliability required from the system, which reduces the overall area covered. Shadow fading has been found in several studies to slightly increase with frequency. From empirical prediction curves presented in [20], which were fitted to data reported by Okumura [10], path loss location variability is estimated to be 1.5 dB higher at 2,500 MHz than at 700 MHz.

B.2.3 Antenna Gain

It has been noted in [5] that, for the same antenna size, the base station antenna’s vertical directivity increases with increasing frequency. This phenomenon leads to a 5.5-dB higher base station antenna gain at 2,500 MHz as compared to 700 MHz. In addition, if antenna diversity schemes are employed, higher diversity gains can theoretically be achieved at the higher frequency for the same antenna separation distance, assuming angular spread to be identical at the two frequencies.