Evolution of 3D User Distribution Models in Real Network Simulator

Sara Bladlund
Abstract

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The report treats the development and evaluation of a three dimensional user distribution model for a real network simulator. The simulator is used to create realistic predictions of real networks with the use of high resolution maps including a building data base and network data and also an advanced radio model for LTE. Previously all simulations have been performed with a two dimensional user distribution, i.e. all users situated on the ground level. Since it is considered plausible that many LTE users will be indoors in buildings with multiple floors, several three dimensional user distribution models with users not only on the ground floor but also on the higher floors has been developed and implemented in the simulator. The models all account for the change in path loss and SINR to be expected and have been compared in computational time and credibility. The simulations show that by the use of such a three dimensional model there is a significant improvement at low loads but at high loads the interference becomes dominant and the results show a deterioration and approaches the results of the ordinary two dimensional model. The seventh and last model to be investigated shows a desirable computational speed that still does not compromise too much with the accuracy and detailing of the model and is therefore recommended for normal use.

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## Contents

1 Introduction 4  
  1.1 Background 4  
  1.2 Previous work 4  
  1.3 Project description 5  

2 Theory 6  
  2.1 Propagation mechanisms 6  
    2.1.1 Free Space Propagation 6  
    2.1.2 Reflection, Refraction and Scattering 7  
    2.1.3 Diffraction 9  
      2.1.3.1 Ideal Knife Edge Diffraction 9  
    2.1.4 Guiding 11  
    2.1.5 Dispersion 11  
  2.2 Propagation Models 11  
    2.2.1 Piecewise Linear (Multislope) Model 12  
    2.2.2 Building Penetration Loss at LOS Conditions in COST 231  
      2.2.2.1 Height Gain in COST 231  
    2.2.3 Outdoor-to-Indoor Propagation in Urban Areas at 1.8Ghz 14  
    2.2.4 Multi-Frequency Path Loss in an Outdoor to Indoor Macro-cellular Scenario 15  
      2.2.4.1 Excess Path Loss Instead of Absolute Values 17  
    2.2.5 Ericsson Urban Model 17  
      2.2.5.1 Indoor Propagation 18  

3 Description of Real Network Simulator and 3D Path Loss Models 20  
  3.1 Short Description of the Real Network Simulator Astrid 20  
    3.1.1 SINR Calculations 21  
      3.1.1.1 SINR Calculations for 3D User Distributions 22  
  3.2 3D Models 22  
    3.2.1 Models without LOS considerations 22  
      3.2.1.1 Description of First Model 22  
      3.2.1.2 Description of Second Model 23
3.2.2 Models With LOS Considerations .......................... 23
  3.2.2.1 Description of Third model .................. 23
  3.2.2.2 Description of Fourth Model .............. 25
  3.2.2.3 Description of Fifth model .............. 25
  3.2.2.4 Description of Sixth model ............ 26
  3.2.2.5 Description of Seventh Model .......... 27
  3.2.2.6 Description of Crowded 3D Model Using Model
       Six ........................................ 29

4 Simulations and Results .................................. 30
  4.1 Comparison of computational times .................. 30
  4.2 Investigation of the G-Matrix .................... 31
  4.3 Models .......................................... 35
      4.3.1 Without LOS Considerations .................. 35
      4.3.1.1 Results from the First Model ........... 35
      4.3.1.2 Results from the Second Model ......... 36
      4.3.2 Models With LOS Considerations .......... 39
        4.3.2.1 Results from the Third Model .......... 39
        4.3.2.2 Results from the Fourth Model ....... 41
        4.3.2.3 Results from the Fifth Model ......... 43
        4.3.2.4 Results from the Sixth Model ........ 43
        4.3.2.5 Results from the Seventh Model ...... 47
        4.3.2.6 Results from Crowded 3D Model Using Model Six 49
      4.3.3 All models in the same plots ............... 51
          4.3.3.1 Path loss .......................... 51
          4.3.3.2 SINR ................................ 51
          4.3.3.3 Mean Bitrates and Capacity ........ 53

5 Discussion and Conclusions .............................. 56
  5.1 Discussion and Conclusions ......................... 56
  5.2 Continuation ..................................... 60

A All Plots .................................................. 68
  A.1 First Model ....................................... 68
    A.1.1 Mean Bitrates and Capacity ................ 68
    A.1.2 SINR ........................................ 69
    A.1.3 Path Loss ................................... 69
  A.2 Second Model ..................................... 70
    A.2.1 Mean Bitrates and Capacity ................ 70
    A.2.2 SINR ........................................ 70
    A.2.3 Path Loss ................................... 71
  A.3 Third Model ....................................... 72
    A.3.1 Mean Bitrates and Capacity ................ 72
    A.3.2 SINR ........................................ 72
    A.3.3 Path Loss ................................... 73
  A.4 Fourth Model ....................................... 74
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.4.1</td>
<td>Mean Bitrates and Capacity</td>
<td>74</td>
</tr>
<tr>
<td>A.4.2</td>
<td>SINR</td>
<td>74</td>
</tr>
<tr>
<td>A.4.3</td>
<td>Path Loss</td>
<td>75</td>
</tr>
<tr>
<td>A.5</td>
<td>Fifth Model</td>
<td>76</td>
</tr>
<tr>
<td>A.5.1</td>
<td>Mean Bitrates and Capacity</td>
<td>76</td>
</tr>
<tr>
<td>A.5.2</td>
<td>SINR</td>
<td>76</td>
</tr>
<tr>
<td>A.5.3</td>
<td>Path Loss</td>
<td>77</td>
</tr>
<tr>
<td>A.6</td>
<td>Fifth Model with Lower Wall Loss Constants</td>
<td>78</td>
</tr>
<tr>
<td>A.6.1</td>
<td>Mean Bitrates and Capacity</td>
<td>78</td>
</tr>
<tr>
<td>A.6.2</td>
<td>SINR</td>
<td>78</td>
</tr>
<tr>
<td>A.6.3</td>
<td>Path Loss</td>
<td>79</td>
</tr>
<tr>
<td>A.7</td>
<td>Sixth Model</td>
<td>80</td>
</tr>
<tr>
<td>A.7.1</td>
<td>Mean Bitrates and Capacity</td>
<td>80</td>
</tr>
<tr>
<td>A.7.2</td>
<td>SINR</td>
<td>80</td>
</tr>
<tr>
<td>A.7.3</td>
<td>Path Loss</td>
<td>81</td>
</tr>
<tr>
<td>A.8</td>
<td>Seventh Model</td>
<td>82</td>
</tr>
<tr>
<td>A.8.1</td>
<td>Mean Bitrates and Capacity</td>
<td>82</td>
</tr>
<tr>
<td>A.8.2</td>
<td>SINR</td>
<td>82</td>
</tr>
<tr>
<td>A.8.3</td>
<td>Path Loss</td>
<td>83</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Background

Real network simulations was started a couple of years ago to get more realistic results instead of hexagon simulations whose results started to diverge to much from measurements performed in real networks. The ongoing work on real network simulations is a cooperation between Ericsson AB and some of the world's leading mobile network operators. It consists of high accuracy path loss predictions from a commercial cell planning tool containing detailed information including a building database, base station site data and antenna patterns and a propagation model that is tuned with drive test measurements from the studied area. In addition to the cell planning tool it also includes an advanced radio model for LTE, support for heterogeneous traffic distributions and different options for distributing the resources of the system. The propagation models can be tuned to fit the type of area it is used for, for example if it is an urban area or a rural. The real network simulator can be used to produce reliable predictions used to analyze and evaluate possible changes made to the network without having to implement them in the operating system. It is considered plausible that many of the LTE users will be indoors and consequently on both higher floors and the ground floor. This motivates the present investigation on how to best include propagation models for such users into the network simulator.

1.2 Previous work

The modelling of outdoor to indoor propagation of radio waves have been investigated and several and sometimes quite different attempts to model it has been proposed, for example [6, 12] to mention two. The task encounters many obstacles and rises many questions. How detailed the model should be is an important balance between accuracy and ease of usage. When modelling indoor propagation, the height of the building also comes in as a factor to be dealt with.
1.3 Project description

All previous predictions have been performed on the ground floor. Since it is considered plausible that many of the LTE users will be indoors and consequently on higher floors than the ground floor, the question arises how this will affect the system. It is known that the attenuation from the base station to the user equipment is dependant of the user equipment height, i.e. the floor on which the user is situated. It is therefore also reasonable to believe that users in tall buildings may experience high interference from neighboring cells. The purpose of this project is to investigate whether a three dimensional distribution for indoor users will impact the result of the simulations of the LTE networks and how such a distribution and its implications can be modeled.
Chapter 2

Theory

2.1 Propagation mechanisms

To describe the methods of radio wave propagation, Maxwell’s equations are usually the starting point. However, a good practical approach is to consider the way power $P \ [\text{W}]$ propagates outwards from a source of energy [1]. An isotropic radiator is a source that radiates uniformly in all directions in a spherical fashion. The power density $p \ [\text{Wm}^{-2}]$ is defined as the transmitted power divided by the surface of the sphere and it enables the calculation of the gain of a radiator. An isotropic radiator does not exist in reality, since it assumes the existence of a point source of energy but it is a useful tool when talking about the directivity of real radiators. The gain $G$ of the radiator is a measure of how much more power density a real radiator is able to transmit in the preferred direction [1].

In reality the radio wave propagates due to interaction between an electrical and a magnetic field. When the strength of a signal is discussed, it is the magnitude of the electric field that is intended. The two fields are perpendicular to each other and to their direction of propagation, at least in free space conditions. Because of this the ray is a useful concept when talking about radio waves. A ray is an imaginary line along the direction of travel of the wave perpendicular to the wave front [2]. What free space condition means and other propagation phenomena will be described below. In general, a wave will experience several of the phenomena simultaneously.

2.1.1 Free Space Propagation

If a transmission is performed well away from the earth’s surface, avoiding any effects from it, then it is said to be in free space propagation conditions. The ray of the signal is under these conditions spread according to an inverse square law [1]. Friis Radiation Formula (2.1) describes a signal being transmitted between
two points spaced \( d \) [m] apart,

\[
P_r = G_r G_t P_t \left( \frac{\lambda}{4\pi d} \right)^2 \text{[W]} \tag{2.1}
\]

In equation (2.1) \( P_t \) [W] is the transmitted power, \( P_r \) [W] is the received power, \( G_r \) is the gain of the receiver and \( G_t \) is the gain of the transmitter. If the logarithm of (2.1) is taken, it can be written as:

\[
10 \log_{10} P_r = 10 \log_{10} G_r + 10 \log_{10} G_t + 10 \log_{10} P_t + 20 \log_{10} \frac{\lambda}{4\pi d} \tag{2.2}
\]

If the power and the gain is related to 1 mW and the gain of an isotropic source respectively, (2.2) can equivalently be expressed as:

\[
P_r \text{ [dBm]} = P_t \text{ [dBm]} + G_r \text{ [dBi]} + G_t \text{ [dBi]} - 20 \log_{10} \frac{4\pi d}{\lambda} \text{ [dB]} \tag{2.3}
\]

The last term in (2.3) is called the free space path loss \( L_{fsp} \), expressed in dB. It represents the loss of a signal transmitted through free space without any obstacles or interfering objects. If \( \lambda \) is replaced by \( \frac{\lambda}{2} \) where \( f \) is the frequency in GHz and \( c \) is the speed of light multiplied by \( 10^9 \) and the terms are separated and the constant is calculated, the following expression is obtained for free space propagation path loss:

\[
L_{fsp} \text{ [dB]} = 32.4 + 20 \log_{10} (d) + 20 \log_{10} (f) \tag{2.4}
\]

This is an equation that is very commonly used in radio propagation contexts, as it is the minimum loss that will occur while transmitting. Equation (2.3) is expressed in words as:

\[
\text{received power} = \text{transmitted power} + \text{antenna gains} - \text{losses} \tag{2.5}
\]

This enables equation (2.5) to be considered as a general expression for describing propagation where losses not only accounts for free space propagation loss but all losses involved in the transmission. This includes for example losses due to reflection, refraction, diffraction and scattering.

### 2.1.2 Reflection, Refraction and Scattering

Reflection describes an incident wave being reflected at an interface between two media and refraction describes an incident wave being transmitted from a medium into another. A wave most often suffers both phenomena. Specular reflection is reflection at a smooth surface and diffuse reflection is reflection at a rough surface. Reflection and refraction changes not only the direction and power of the wave, but also the polarization which is an important property of a wave as it affects the ability to transfer power.

The specular case is efficiently described by Snell’s laws, the law of reflection (2.6) and the law of refraction (2.7). The index of refraction \( n \) of a material is
heavily dependent on the frequency of the incident wave. The angles $\Theta_i$, $\Theta_r$, and $\Theta_t$ are the angles between the normal of the surface and the incident, reflected and refracted/transmitted wave respectively.

$$\Theta_i = \Theta_r$$  \hspace{1cm} (2.6)

$$n_1 \cos \Theta_i = n_2 \cos \Theta_t$$  \hspace{1cm} (2.7)

Diffuse reflection and refraction occurs when a surface is not ideally smooth, which is generally the case. Whether a surface is considered smooth or rough, the level of roughness and how much it affects an incident wave is of course dependent on the material, but also on the wavelength $\lambda$ of the wave. Also the angle with which it imposes on the surface is important [1]. A surface is generally thought of as smooth if its vertical height variation $h$ satisfies the Rayleigh criterion;

$$h < \frac{\lambda}{8 \cos \Theta_i}$$  \hspace{1cm} (2.8)

where $\Theta_i$ is the angle between the incident ray and the normal of the surface, see figure 2.2. Equation (2.8) implies that most manufactured surfaces can be regarded as smooth and treated as such for wavelengths $\lambda$ at the decimeter scale. However, when the wave strikes a rough surface or heterogeneities with small dimensions compared to the wavelength such as soil or trees the reflection can no longer be treated as specular. From such surfaces, the outgoing wave
is scattered, see figure 2.2. Scattering means that the energy of the wave is distributed in several directions [3] thus reducing the power in the ideal reflected direction. However, scattering can sometimes be desired as it provides a good spreading of the wave.

2.1.3 Diffraction

The way electromagnetic waves behave when they impinge on obstacles or apertures with dimensions larger than the wavelength is described by the propagation phenomenon known as diffraction. To understand it, it is easiest to abandon the ray description and instead consider the wavefronts of the waves. According to Huygens's principle all points on a wavefront can be regarded as an isotropic radiator radiating spherically, see figure 2.3. This implicates that the future behavior can be synthesized from the interference of the fields from these imaginary secondary radiators [1]. Diffraction enables radiation to "bend" around corners at the expenses of energy loss in the wave. It arises from many occurrences, for example the curvature of the earth, hilly or irregular terrain, building edges or obstructions blocking the line of sight [LOS] path between the receiver and the transmitter [4].

2.1.3.1 Ideal Knife Edge Diffraction

Diffraction can be very demanding to model and therefore the approximate Fresnel knife edge diffraction is commonly used [4]. The ideal knife edge diffraction use the ray concept. The geometry of the model with one single knife edge and obstructed LOS between the transmitter and the receiver is shown in figure 2.4 where the diffracting object is assumed to be asymptotically thin and infinitely
Figure 2.3: Diffraction of energy from a wavefront as it impinges on an obstacle. The gray circles symbolize the imaginary wavefronts of the point sources. The wavefront thus curves around the corner.

\[ C(\nu) = \int_{0}^{\nu} \cos \frac{\pi t^2}{2} dt \]

\[ S(\nu) = \int_{0}^{\nu} \sin \frac{\pi t^2}{2} dt \]

where the dimensionless Fresnel parameter \( \nu \) is defined as:

\[ \nu = \frac{h}{d + \frac{d'}{dd'}} \sqrt{\frac{2}{\lambda \left( \frac{1}{d} + \frac{1}{d'} \right)}} \]
The distances $d$ [m], $d'$ [m] and $h$ [m] are defined in figure 2.4 and $\lambda$ [m] is the wavelength [3]. The Fresnel parameter expresses the obstruction by the obstacle of the LOS. The development of the Fresnel integrals in series leads to approximate relations for the attenuation relative free space due to the obstructing object. One example of such an approximation is equation (2.12) found in [4].

$$L(\nu) \text{ [dB]} = \begin{cases} 
20 \log_{10} (0.5 - 0.62\nu) & -0.8 \leq \nu < 0 \\
20 \log_{10} (0.5e^{-0.95\nu}) & 0 \leq \nu < 1 \\
20 \log_{10} \left(0.4 - \sqrt{0.1184 - (0.38 - 0.1\nu)^2}\right) & 1 \leq \nu \leq 2.4 \\
20 \log_{10} (0.255/\nu) & \nu > 2.4
\end{cases}$$

(2.12)

There are also models for multiple diffracting edges and even for rounded obstacles [3].

### 2.1.4 Guiding

Some environmental features like street canyons, tunnels and other building constructions act like wave guides for radio waves. This is the case especially when the wavelength is very small compared to the cross section of the feature [3]. A wave guide is in the electromagnetic theory defined as a tube of perfectly conducting material with open ends and constant cross section [5]. The tube can be of arbitrary shape but most often the square or the circular shape is considered. A wave propagating inside a wave guide is restricted to certain modes due to the fact that the wave has to terminate at the walls of the guide. This implies that there is a minimum wavelength for signals propagating inside a specific wave guide [1]. The corresponding frequency is known as the cut off frequency, that is to say the wave guide acts as a high pass filter.

### 2.1.5 Dispersion

Dispersion denotes frequency dependent effects in wave propagation. In the presence of dispersion, wave velocity is no longer uniquely defined. This gives rise to the distinction between phase velocity, the velocity with which a point of constant phase moves and group velocity, the velocity with which any modulation of the wave travels [1]. A well known effect of phase velocity dispersion is the color dependence of light refraction that can be observed in prisms and rainbows. Dispersion may be caused by geometric boundaries such as wave guides or by interaction between waves.

### 2.2 Propagation Models

As a result of the propagation phenomena described above, numerous propagation models have been developed, often for a specific scenario and circumstances. In this section some of the models that have been important parts of the creation
of the three dimensional 3D user distribution models treated in this report, are presented.

2.2.1 Piecewise Linear (Multislope) Model

The piecewise linear model, also called the multislope model, relates dB loss to log distance. It is an empirical method for modeling path loss used in both outdoor and indoor cases [4]. The area of interest is divided into \( N \) different regions. The regions \( s_1, \ldots, s_N \) are separated by breakpoints \( (d_1, d_2, \ldots, d_{N-1}) \) and each region has a specific linear slope. The breakpoints and the slopes have to be decided in the model design. Equation (2.13) below describes a special case of the multislope model, the dual slope model. In the dual slope model, only two path loss regions are considered. The first region with slope \( \gamma_1 \) stretches from a reference distance \( d_0 \) [m] to a critical distance \( d_c \) [m] where the path loss exponent changes to \( \gamma_2 \).

\[
P_r (d) \, [\text{dB}] = \begin{cases} 
P_t + K - 10\gamma_1 \log_{10} \left( \frac{d}{d_0} \right) & d_0 \leq d \leq d_c \\ P_t + K - 10\gamma_2 \log_{10} \left( \frac{d}{d_c} \right) & d > d_c \\ \end{cases}
\]

In equation (2.13) \( P_r \) [dB] is the received power, \( P_t \) [dB] is the transmitted power and \( K \) [dB] is a constant path loss factor. The path loss exponents \( K \) and \( d_c \) are usually found through a regression fit to empirical data.

2.2.2 Building Penetration Loss at LOS Conditions in COST 231

The model proposed in [6] is an attempt to describe many different propagation models proposed by the COST 231 participants. The model assumes free space propagation path loss between the external antenna and the illuminated wall and is not based on an outdoor reference level.

\[
L \, [\text{dB}] = 32.4 + 20 \log_{10} (f) + 20 \log_{10} (S + d) + W_c + W G_e \left(1 - \frac{D}{S}\right)^2 + \max(\Gamma_1, \Gamma_2)
\]

\[
\begin{aligned}
\Gamma_1 &= W_i \cdot p \\
\Gamma_1 &= \beta \cdot d \\
\Gamma_2 &= \alpha \cdot (d - 2) \cdot \left(1 - \frac{D}{S}\right)^2
\end{aligned}
\]

(2.14)  
(2.15)  
(2.16)

The model parameters, the angle \( \theta \) [deg] and the distances \( S \) [m], \( D \) [m] and \( d \) [m] are defined in figure 2.5. The frequency \( f \) is in GHz and \( W_c \) is the loss in dB in the externally illuminated wall at perpendicular penetration (\( \theta = 90 \) [deg]). The only time when \( \theta = 90 \) [deg] is when \( S \) and \( D \) are equal, that is when
Figure 2.5: Definition of angles and distances. The building is seen from above.

the external antenna is located at the same height as the floor height and at a perpendicular distance from the wall. The additional loss in dB in the external wall when $\theta = 0$ [deg] is represented by $W G_\alpha, W_\beta [\text{dB}]$ in (2.15) is the loss in the internal walls and $p$ is the number of indoor walls. In case there is no internal walls, then the indoor loss is decided with an indoor slope in dB/m. In equation (2.15), the first expression for $\Gamma_1$ can be replaced by the second, $\beta \cdot d$ where $\beta$ is a slope in dB/m, if the average indoor wall loss and the average distance between the indoor walls are known. Finally $\alpha$ is a slope constant in dB/m.

2.2.2.1 Height Gain in COST 231

The outside-to-inside penetration loss at different floor levels is sometimes found to decrease with increasing floor levels, something that is also discussed in [6]. The dependence is called floor height gain and is given in dB/m. Gain in this context is path gain, the inverse of the path loss, and is not to be confused with antenna gains as described in section 2.1 on page 6. The sum of the outside reference path loss value and the height gain loss, can never be less than the free space propagation path loss, since that would be highly unrealistic. The floor height gain ceases to be applicable at floor levels that is considerably above the average height of the neighboring buildings. The most notable floor height gain is found in non line of sights [NLOS] conditions, when the main part of the received signal power originates from rays that due to reflections and diffraction have propagated down from the surrounding roof level. This is usually the case in macro-cellular\(^1\) environments with the base station [BS] at a height greater than the average height of the neighboring buildings.

\(^1\)Macro cells are defined by the height and transmitting power of the employed antennas. Heights are above the average surrounding building heights and the power is in the range of 40 to 80 W.
2.2.3 Outdoor-to-Indoor Propagation in Urban Areas at 1.8Ghz

In [7] a model treating outdoor to indoor propagation is proposed. It is partly based on [6] and consists of two parts, one empirical and one semiempirical. Both parts use the height gain model described below in some form.

The height gain model in short uses the path loss predicted at ground floor to decide path loss at higher floors. Each floor is considered to be 3 m high and subtracts 3 dB from the path loss, thereby rendering the resulting path loss at higher floors lesser than at ground level. The model is considered to be valid up to floor number 5 if the ground floor is set to 0.

The empirical model contains three different parts. The first is the calculation rules describing how the indoor path loss is derived from the outdoor path loss of all surrounding pixels. The second is an empirical penetration loss factor describing the signal strength difference inside and outside the building and the third is the empirical height gain model described above.

First the bins to be considered has to be decided. The set $P_{in}$ contains all $N$ bins belonging to the same building with at least one neighboring outdoor bin. Then, for every bin $P_{b}$ in $P_{in}$ the set $P_{out,k}$ of all neighboring outdoor pixels is determined, see figure 2.6. Equation (2.17) calculates $L_{building,floor}$ [dB] which is the mean indoor path loss for a particular building and floor. It is determined by averaging the $N$ path loss values in $L_{in,k}$ [dB].

$$L_{building,floor} \text{ [dB]} = \frac{\sum_{k=1}^{N} L_{in,k}}{N} \quad (2.17)$$

$$L_{in,k} \text{ [dB]} = \min \left( L_{fsp,k} + L_{emp}, \hat{L}_{in,k} \right) \quad (2.18)$$

$$\hat{L}_{in,k} \text{ [dB]} = \min_{\forall i, P_{i} \in P_{out,k}} (L_{k,i}) + L_{pen} \quad (2.19)$$

$$L_{pen} \text{ [dB]} = L_{emp} - G_{h} \quad (2.20)$$

To calculate $L_{in,k}$ the help variable $\hat{L}_{in,k}$ is used. It is the sum of the minimum outdoor path loss of all $P_{k,i} \in P_{out,k}$ and the penetration loss $L_{pen}$. The penetration loss $L_{pen}$ is the empirical loss factor $L_{emp}$ reduced by the height gain.
The path loss $L_{in,k}$ is then taken as the minimum of $\hat{L}_{in,k}$ and the sum of free space path loss $L_{fsp}$, see equation (2.4) on page 7, and $L_{emp}$. This limits $L_{in,k}$ to realistic physical values. The variable $L_{k,i}$ is the path loss calculated by the outdoor model at bin $P_{k,i}$. The value of $L_{emp}$ is set to between 19 and 22 dB, values that are deduced from measurements.

The semiempirical model improves on the empirical model by introducing some deterministic components if LOS between the BS and at least some parts of the building exist. The model starts with distinguishing LOS and NLOS for each bin on every floor. Then two separate methods for path loss calculation in case of LOS or NLOS are deployed. If the bins have LOS then the path loss is calculated as

$$L_{in,LOS,k} = 32.4 + 20 \log_{10} (f) + 20 \log_{10} (s + d) + L_{perp} + L_{par} \left(1 - \frac{D}{S}\right)^2$$  \hspace{1cm} (2.21)

which is free space propagation path loss with added loss for entering the house. The distances $d$, $S$, and $D$ all in m are defined in figure 2.5 on page 13. The empirical penetration factor describing penetration loss for perpendicular incidence of the wave is represented by $L_{perp}$ and $L_{par}$ is an empirical penetration factor describing an additional penetration loss factor for $\theta \to 0$ [deg]. The angle $\theta$ is defined in figure 2.5.

The path loss in the NLOS case is calculated as in the empirical model with the small difference that when calculating the floor height gain the maximum number of floors is limited to the number of floors which corresponds to the mean building height along the path between the BS and the mobile station [MS].

### 2.2.4 Multi-Frequency Path Loss in an Outdoor to Indoor Macrocellular Scenario

The article [9] describes the connection between different frequencies and the excess path loss they generate. The excess path loss $L_E$ is defined in equation (2.22) as the loss relative to free space propagation path loss $L_{fsp}$ (see equation (2.4)),

$$L_E \text{ [dB]} = L_P - L_{fsp}$$  \hspace{1cm} (2.22)

where $L_P \text{ [dB]}$ is the path loss as defined in equation (2.23),

$$L_P \text{ [dB]} = P_t - P_r + G_t + G_r$$  \hspace{1cm} (2.23)

The variables $P_t$ [W] and $P_r$ [W] are the transmitted and received power respectively and $G_t$ and $G_r$ are the antenna gains of the transmitter and receiver respectively. An advantage of using excess loss instead of absolute loss is that the frequency dependent aperture of the receiver antenna, which does not reflect any environmental propagation properties, is removed.
The article also describes loss dependency on floor levels and proposes a simple empirical model to model the dependency as an average building penetration loss $L$ [dB]:

$$L_{\text{los}} [\text{dB}] = \frac{10}{a} \log_{10} \left( 10^{-\frac{n_{\text{fl}} G_{\text{fl}}}{10}} + 10^{-\frac{n_{\text{flb}} G_{\text{flb}}}{10}} \right) + n_{\text{flb}} G_{\text{fl}} + L_{\text{los}} \quad (2.24)$$

$$L_{\text{los}} [\text{dB}] = L_{\text{mes, in}} - L_{\text{fsp, out}} \quad (2.25)$$

The model is based on the building penetration loss at LOS conditions, $L_{\text{los}}$ as defined in equation (2.25), and the corresponding gain with floor level in NLOS conditions, $G_{\text{fl}}$ [dB]. The floor number is represented by $n_{\text{fl}}$ and $n_{\text{flb}}$ is the floor number for the lowest floor at which there is LOS conditions towards the transmitter. $a$ is a parameter adjusting the size of the model transition zone between the LOS and the NLOS conditions. The loss factor $L_{\text{mes, in}}$ is the measured value inside the building and $L_{\text{fsp, out}}$ is the theoretical outside free space propagation path loss reference value. The model in equation (2.24) has been fitted to measurements made inside and outside buildings [9] and the resulting values of $G_{\text{fl}}$ is between 1 and 4 [dB/floor] and of $L_{\text{los}}$ between 20 and 35 [dB].

The value of $L_{\text{los}}$ can not always be measured since some buildings never reach the required height. In such cases it is suggested that $L_{\text{los}}$ is taken as $L_{\text{diff}}$ which is the difference between the measured loss indoors and outdoors at ground level. In cases when this is not a possibility either, $L_{\text{los}}$ is suggested to be set as a parameter with a value in the range of the values measured in [9] which are in the range of 20-30 dB.
2.2.4.1 Excess Path Loss Instead of Absolute Values

In [10] two ways of calculating penetration loss is compared. The first is when penetration loss is determined using the difference between the path loss in dB from measurements in the building and reference measurements outside the building. The second is to use the theoretical free space propagation path loss as the outside reference loss instead of measured reference levels. The article suggests the latter as the more accurate model. For details on how the measurements were made, see [10]. Measured penetration losses are found to vary between 5dB and 30dB. If instead a theoretical reference value is used, two major differences appear. First that the penetration loss increases when the theoretical path loss value is used as reference value, and the second is that the spread of penetration loss values decreases to instead vary between 23dB and 32dB. By using the theoretical values instead of the measured, abnormalities can be avoided and the penetration values becomes more suitable for modelling.

Another result presented is that difference in penetration loss between different frequencies, in this case 900MHz and 1700MHz, is significantly decreased using the theoretical values as reference values.

2.2.5 Ericsson Urban Model

The Ericsson Urban Model is a concept that combines two different wave propagation algorithms, the half screen model and the recursive microcell model [8].

The half-screen model is used for calculating the propagation above rooftops. Obstacles such as buildings and trees between the BS and the MS are modelled with a number of screens with heights correlated to the heights of the obstacles. The path loss $L_{above}$ [dB] is then calculated using a multiple knife-edge approach, see part 2.1.3.1 on page 9. Two kinds of screens are employed to describe the profile of the environment, permanent screens that are placed in a statistical way, and temporary screens that are placed in a deterministic way. The permanent screens are used to describe the environment along the calculation profile in a general way and the temporary screens will describe details of the environment more accurately, near the mobile antenna. For example, the screens modelling a forest would typically be set in a statistical way, while screens modeling buildings would be set deterministically.

The recursive microcell model is used for calculating the propagation between buildings, for example along streets. For defining the propagation paths, the exact locations of buildings according to the building data base, are used. The path loss $L_{below}$ [dB] is calculated by determining the so called illusory distance between the BS and the MS in a street system. The illusory distance is determined with a recursive method, using input data from a street system and takes into consideration the multiple street crossings and turns that are present.

The resulting path loss arising from the Urban Model $L_{urban}$ [dB] is the least of the two values generated by the two models,
\[ L_{urban} \ [\text{dB}] = \min (L_{above}, L_{below}) \]  

Close to the basestation and in LOS cases, the microcell model dominates and only the value of \( L_{below} \) is used. Otherwise it is the half screen model that dominates and only the value of \( L_{above} \) is used. In reality both values always contribute to the total path loss but the effects of this approximation are small enough not to be significant.

The model is considered valid for frequencies from 450 MHz up to 2200 MHz and at distances both close to and far from, at least 50 km, the BS antenna. It is also considered valid for high MS heights.

### 2.2.5.1 Indoor Propagation

For indoor propagation in the Ericsson Urban Model, given it has access to a detailed land use map containing the locations and heights of buildings, a special indoor model with the following properties is used. An indoor path loss value for a particular bin is calculated by first deciding the four outdoor bins closest outside the building to the north, the south, the east and the west of the indoor bin, see Figure 2.8. The path loss values of these bins have been chosen according to equation (2.27).

\[ L_{out} \ [\text{dB}] = \max (L_{urban}, L_{fsp} + W_{ge}) \]  

The path loss \( L_{urban} \ [\text{dB}] \) is a value calculated by the Urban Model, which is treated above and \( L_{fsp} \ [\text{dB}] \) is the free space propagation to that outdoor bin from the basestation calculated according to equation (2.4). The additional loss \( W_{ge} \ [\text{dB}] \) is wall loss that accounts for extra losses due to a grazing incidence angle. The graze constant only occurs when a LOS path is assumed, since NLOS paths often are scattered from multiple directions, leaving at least one that has a perpendicular incidence angle, while LOS paths only have one incidence angle and it can’t be assumed to be perpendicular to the building wall. From the path loss values of these outside bins, an external wall loss constant \( W_{e} \ [\text{dB}] \) is subtracted and then a loss per meter, a so called slope, \( \alpha \ [\text{dB/m}] \) is used to account for the additional path loss of the final indoor distance \( s \ [\text{m}] \), leaving the indoor path loss \( L_{in} \ [\text{dB}] \) as in equation (2.28).

\[ L_{in} \ [\text{dB}] = L_{out} \ [\text{dB}] + W_{e} + s \cdot \alpha \]  

The indoor path loss value is calculated for all four starting positions and then the best indoor path loss is used.
Figure 2.8: Indoor bin and the four surrounding outdoor bins considered as starting positions for indoor propagation.
Chapter 3

Description of Real Network Simulator and 3D Path Loss Models

In the following chapters, the concept of path loss will be frequently discussed, it is therefore important to define what is intended with this concept. Path loss is according to ITU\(^1\) defined as losses due only to the phenomena described in section 2.1 on page 6 and similar propagation factors. In the following chapters also antenna and other equipment properties are included in the calculations of the total path loss. ITU would classify that as system loss.

3.1 Short Description of the Real Network Simulator Astrid

TEMs CellPlanner [TCP]\(^2\) is a cell planning tool that can be used for path loss predictions of radio networks. In the predictions performed for this rapport it uses the model described in section 2.2.5 on page 17. The path loss predictions consider terrain and building information depending on the level of details in the map data employed. For example, in the predictions performed for this rapport the positions and lobe patterns of the antenna and building locations and heights are known with a precision of squares with the sides of 5 m, called bins.

The data is exported to the stationary MATLAB real network simulator called Astrid. Astrid uses an advanced radio model specific for LTE technologies. It enables simulations of fairly large, inhomogeneous networks with traffic distributions with a specified percentage of indoor and outdoor user equipment

\(^{1}\)ITU is the UN agency for information and communication technologies.

\(^{2}\)Recently changed to MENTUM CellPlanner for new releases of the program.
Astrid also enables different traffic levels between cells. The simulation considers a restricted area of a large city. In order to model realistic interference situations at all simulated cells, interference contributions from outside of the restricted area have to be considered, see figure 3.1.

The predictions in Astrid can be performed at different loads. The load is the ratio between used and total resources. If all the resources are allocated, meaning that one UE or BS per cell is transmitting with full bandwidth and full power all the time, the load is 100%. Should the load be lower, then the transmission is only ongoing part of the time. In each instant, only one UE or BS is active in every cell. Every simulation consists of several time instants. The resources can be administered in different ways but in this report they have been distributed so that all UE regardless of their SINR will get equal access to the resources. This means that UE with poor SINR will transmit and receive less data than a UE with good SINR. The capacity of the system is closely entwined with the load. A system capable of delivering a certain bitrate for a specific time i.e. a specific load has a higher capacity than a system capable of delivering the same bitrate for lesser periods of time, i.e. at lower loads.

### 3.1.1 SINR Calculations

The SINR calculations differs between the up link [UL] and the down link [DL]. The interferers in the DL are BS from surrounding cells. They are stationary and therefore their location and number are easier to predict than the interferers in the UL. In the UL the interferers are UE in the neighboring cells and therefore mobile which makes the interference hard to predict. The DL interference is based on path gain predictions from interfering cells to the considered cell, and information about BS powers from interfering cells. A stated power level is used for all load situations.

The UL interference is modeled by introducing a Monte Carlo distribution of UE to create interference. This distribution of UE is repeated several times to create a statistically credible scenario. Equation (3.1) describes the SINR calculation of a bin. The variable $P [W]$ is the power transmitted from the BS, $g$ is the path gain i.e the inverse of path loss, calculated for each cell to each bin and $N [W]$ is the noise.

![Figure 3.1: Analysis area](image)

---

21
\[ SINR_{bin} = \frac{P_{\text{best cell}} \cdot g_{\text{best cell}}}{\sum_{i \neq \text{best cell}} P_i \cdot g_i + N} \]  \hspace{1cm} (3.1)

The SINR values are translated to bitrates according to a link to system model relating SINR to bitrates.

The results of a simulation can be presented as the result in every bin, this is referred to as binprobing. The alternative is to only present the bins selected by the Monte Carlo process. This is referred to as user distribution.

### 3.1.1.1 SINR Calculations for 3D User Distributions

The SINR calculations are essentially the same as before when the bins or UE are distributed in a 3D fashion. The difference is that as the height of a bin is increased, there will be some decrease in path loss and this applies for both the connection between the UE and its serving BS as well as the UE and interfering BS or BS and interfering UE. This has been modeled by giving the gain calculated between the UE and its serving BS to not only that path loss prediction but also to all the interferers path loss predictions. This might be a slightly pessimistic assumption but since no measurements addressing the issue has been made regarding this, it is the best approximation available.

### 3.2 3D Models

In this section the structure and concept of the 3D user distribution models that has been created are described. They are described in the chronological order that they were created and tested and therefore simply named as model one to model seven.

#### 3.2.1 Models without LOS considerations

The first two models does not take any LOS calculations into consideration.

#### 3.2.1.1 Description of First Model

This model is based on the article [7], that describes outdoor and outdoor-to-indoor propagation. In the article, measurements were made in the towns of Cologne and Leipzig and a model was created, tested and compared to the measured data. They found the predictions made by their model to be fairly accurate compared to their measurements. Not all of their model is used here, but some assumptions concerning building and floor properties.

The indoor bins are given a floor number according to a uniform random distribution from ground floor, floor 1, and up to a specific maximum floor level. This maximum is given by a parameter called maxfloor. Maxfloor is set to 6 in the simulations and each floor is considered to be 3m high, both values in accordance with [7], see section 2.2.3 on page 14.

22
Figure 3.2: Floor distribution. In the first model the height of all buildings is 6 floors. In all other models the height of the buildings varies according to the building data.

The path loss is calculated in TCP at ground level, which in this case means 1.5 m above ground, for all bins, indoor and outdoor. For the indoor bins, 3 dB path gain is added for each floor above ground floor. The model does not separate indoor bins at the edge of the house from indoor bins located in the middle of the house, they are all given the same floor height gain of 3 dB/floor.

3.2.1.2 Description of Second Model

The second model is almost identical to the first. The difference lies in the parameter maxflo. Maxflo is not one fixed value for all buildings in this model, but the highest possible floor in every building. Since the number of floors are not known from the building data base, but the building heights are, every floor is assumed to be 3 m high as in model one and in all models to follow. Floornumbers are distributed randomly according to a uniform distribution from ground floor, to the maximum floor of the building and all indoor bins are again given a gain of 3 dB/floor for every floor above ground floor.

3.2.2 Models With LOS Considerations

The following models take the existence of a LOS between building and BS into consideration.

3.2.2.1 Description of Third model

This third model investigates whether a bin has a LOS to the base station it uses, and if it has, at what height that occurs. The LOS-information is later used to decide what kind of height gain a particular bin should have. The floors are distributed as in the second model, up to the maximum height of the building, with an assumed floor height of 3 m. Each bin, now given a floor, then gets a floor height gain that depends on whether that particular floor has a LOS
or not. This idea comes from the same source as before [7]. The assumption is that once a floor has LOS, all higher floors also have LOS. The calculation of LOS or NLOS are done between a bin and its serving BS. The bin is first assumed to be at ground level, 1.5 m above ground. An imaginary straight line is drawn between the BS and the bin. If any intermediate building obstructs the line, then its stated that the bin does not have LOS conditions. This procedure is then repeated at 3 m intervals, i.e. at the floors, until either a LOS has been confirmed or the building run out of floors. Only bins that are situated on the edge of a building can have LOS.

A bin without LOS at the floor given, gets the usual 3 dB/floor floor height gain. The bins with LOS at the given floor get a path gain value interpolated from predictions in TCP instead. One prediction is made at ground level, one at a height that corresponds to 6 floors, i.e. 15 m, and one is made at a height of 40 m and then the path loss values in between are interpolated linearly in dB\(^3\). When choosing the height for the upper prediction level, the values found in table 3.1 were considered. The table describes the distribution of building heights in the considered area. The height chosen, 40 m, is high enough to include almost all of the indoor bins (only 2.03 % of the bins belong to higher buildings), but not so high that the angle between the floor and the base station becomes too large. It is important that the upper height is not too high since a too great an angle would cause the pattern of the antenna lobe to increase the path loss in a manner that is no longer probable to be linear in dB. The assumption of 40 m being a good choice will be further investigated in section 4.2 on page 31.

\(^3\)Note that the LOS calculations are performed 1.5 m up on every floor, while 15 m is at the bottom of a floor. This is compensated by using an interpolated value that is 1 m up. The decrease from 1.5 m to 1 m is considered reasonable given that UE at higher floors might be at a working desk height.
Table 3.1: Building height distributions

<table>
<thead>
<tr>
<th>percent of all bins [%] (total number of bins 260516)</th>
<th>percent of indoor bins [%]</th>
<th>number of bins higher than X (total number of indoor bins 119647)</th>
<th>X [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0748</td>
<td>0.1647</td>
<td>197</td>
<td>90</td>
</tr>
<tr>
<td>0.0964</td>
<td>0.2123</td>
<td>254</td>
<td>80</td>
</tr>
<tr>
<td>0.1150</td>
<td>0.2332</td>
<td>303</td>
<td>70</td>
</tr>
<tr>
<td>0.2178</td>
<td>0.4797</td>
<td>574</td>
<td>60</td>
</tr>
<tr>
<td>0.3419</td>
<td>0.7530</td>
<td>901</td>
<td>50</td>
</tr>
<tr>
<td>0.9210</td>
<td>2.0285</td>
<td>2427</td>
<td>40</td>
</tr>
<tr>
<td>5.4653</td>
<td>12.0371</td>
<td>14402</td>
<td>30</td>
</tr>
<tr>
<td>23.8946</td>
<td>52.3265</td>
<td>62906</td>
<td>20</td>
</tr>
<tr>
<td>43.1146</td>
<td>94.9577</td>
<td>113614</td>
<td>10</td>
</tr>
<tr>
<td>45.3786</td>
<td>99.9440</td>
<td>119580</td>
<td>5</td>
</tr>
</tbody>
</table>

3.2.2.2 Description of Fourth Model

This model is basically the same as the third model in that it separates the indoor bins with LOS from those with NLOS. The LOS bins are also found in the same manner and the floors are distributed to all bins as in model three. The difference is that the NLOS bins are given their path loss value in a different way. Given a particular floor are associated with the LOS bins at that floor. The NLOS bins path loss values are then calculated according to

\[
L_k [\text{dB}] = L_{k,\text{los}} [\text{dB}] + d_k \cdot \alpha
\]

where \(d_k [\text{m}]\) is the distance from the NLOS bin to LOS bin number \(k\) on that floor with path loss value \(L_{k,\text{los}}\). The value of the loss factor \(\alpha\) is 0.6 dB/m as suggested in [6]. The least of the calculated path losses \(L\) is then chosen as the path loss value for that NLOS bin. The value for \(L_{k,\text{los}}\) is taken from the interpolated values as described in the previous section. This difference between model three and four was constructed to make sure that the inner values, supposedly dependant on the LOS to bins situated at the edge of the building actually had an impact on the choice of bins to start from when calculating path loss for indoor bins.

All NLOS bins without a LOS bin on the same floor is given a floor height gain of 3 dB/floor for every floor above ground floor.

3.2.2.3 Description of Fifth model

In this model, the LOS calculations differs slightly from model three and 4. Instead of using indoor bins situated on the edge of the buildings, an imaginary
shell of outdoor bins was created for each house. This shell of outdoor bins is then used for the LOS calculations described above. This change is done to avoid the outdoor-to-indoor calculations made in TCP, see 2.2.5.1 on page 18 and it entails the need to introduce a new loss to account for building penetration losses since those are no longer contributed by the path loss values from TCP. Therefore equation (3.3) used in model four is replaced by equation (3.4) in this model.

\[ L [\text{dB}] = \min_k (L_k) + W_e + W_{ge} \] (3.4)

The variable \( W_e [\text{dB}] \) is the external wall loss factor and \( W_{ge} [\text{dB}] \) is the grazing angle loss factor. No vector information about the buildings are accessible, disabling the calculation of angle of arrival for the LOS rays reaching the building. Therefore it is not possible to tune the grazing angles loss and the worst case, rays arriving almost parallel to the building, is assumed for all bins. In the first set of simulations, \( W_e = 12 [\text{dB}] \) and \( W_{ge} = 20 [\text{dB}] \). Note that \( L_{k,los} \) in (3.4) is changed from being values predicted to the inside of the building, to being values predicted to just outside the building.

The second set of simulations use a lower value for the grazing angle loss factor. Instead of 20 dB, \( W_{ge} = 12 [\text{dB}] \). This could be considered as if it uses a kind of average value instead of the worst case value.

### 3.2.2.4 Description of Sixth model

Section 2.2.4 on page 15 describes a simple model for outdoor to indoor loss that is used as a base for this sixth model. The average building penetration loss \( L [\text{dB}] \) is calculated as in equation (2.24) on page 16. The value of \( L \) is only specific for the floor, not for every bin, meaning that all bins on the floor get the same floor height gain. However, since the gain is added to indoor predictions made by TCP on ground floor, there will still be a gradient inside with most loss in the middle of the building. The floor gain constant \( G_{Fl} \) is set to 3 dB as in previous models, since it was in the range proposed in is in [9] and coincides with the previously used values, enabling an easier comparison between models. The value of \( L_{LOS} \) is set to 24.5 dB which is in the range suggested in section 2.2.4 on page 15. If \( L_{LOS} \) is thought of as a replacement for wall loss constants and grazing angle losses as in 3.2.2.3 on the preceding page, then the \( L_{LOS} \) value is quite lower, maybe implying that a decrease of the additional losses might be more suitable. The floor number \( n_{Fl} \) is assigned to the indoor bins as in all previous models except the first. The variable \( n_{Fl,lb} \) describing the lowest floor at which a building has LOS, is calculated for every building. The LOS calculations are performed as in model four. It could also have been done as in model five since the calculations only are used to set the variable \( n_{Fl,lb} \) and does not contribute to the choice or outdoor bins used for indoor predictions. When a path loss value for an indoor bin is to be predicted, the value of \( L \) corresponding to that bin, or really, the floor that bin is on, is calculated. It is then added to the theoretical path loss in case of free space propagation, see
Figure 3.4: Cdf of building penetration loss $L_{LOS}$ (to the left) and floor height gain $G_{FI}$.

(2.4) on page 7, of the nearest outdoor bin giving the total path loss $L_{tot}$ as in equation (3.5). The calculations are also performed at ground level, i.e. with all the bins at ground floor. This is to enable the difference to be calculated and then be used as floor height gain added to the predictions made by TCP.

$$L_{tot} = L + L_{fsp}$$  \hspace{1cm} (3.5)

3.2.2.5 Description of Seventh Model

The seventh model is identical to model six in everything except in two things. The first is that the parameters $L_{LOS}$ and $G_{FI}$ are not constant anymore but distributed to every bin according to a Gaussian distribution with their previous values as their new mean value. The standard deviation of $L_{LOS}$ is three and of $G_{FI}$ it is one. These values are selected to keep the parameters within the range proposed in [9]. The cdf curves of $L_{LOS}$ and $G_{FI}$ can be seen in figure 3.4. The second difference is that there is an additional loss added due to the antenna tilt and vertical lobe patterns of the serving BS. The lobe patterns affect the result since they direct the effect of the BS in certain angles that might be far off from the LOS between the BS and a bin at a certain level. The same lobe pattern has been used for all BS’s antennas. This is an approximation since the lobe patterns really differ slightly, however the lobe patterns are similar enough for the result to be significant for the use of such a lobe pattern. Should the effect be major, it might be interesting to use the exact lobe pattern for all antennas.

The used antenna lobe pattern can be seen in figure 3.5. As is evident there, the electrical tilt of that antenna is 6 degrees, that is 75% of all the antennas in the restricted area have, which motivates the choice of typical antenna. The loss due to the lobe pattern is calculated in the following manner: The angle between the bin and its serving BS is calculated. If the BS serving the bin has a mechanical tilt, that angle is added to the calculated angle. The resulting angle is subtracted from 360 degrees, this is done to adopt the values to the lobe pattern definition of angles that is, as seen in figure 3.5, opposite to the
Figure 3.5: The vertical lobe pattern used to represent all BS in model seven. The antenna gain is 16.0 dBi.
Figure 3.6: Floor distribution in the crowded 3D model. The path loss at ground floor in building A, B and C will be counted 8, 4 and 6 times respectively, to create a data series for the ground floor predictions comparable to the higher level predictions that will be performed once for every floor in a building.

convention. The result is the angle used to find the corresponding additional loss $L_{lobe}$ due to the angular deviation from the lobe maximum. This loss need to be related to the antenna gain $G_{antenna}$ which for the antenna used is 16.0 dBi. Equation (3.6) describes the calculations. Note that $L$ is replaced by $L_G$ since two parameters used to calculate it is Gaussian distributed.

\[
L_{tot, lobe} = L_G + L_{fsp} - G_{antenna} + L_{lobe}
\]

(3.6)

3.2.2.6 Description of Crowded 3D Model Using Model Six

This model is slightly different from all other models. It is not a part of Astrid but completely separate which means that it only calculate path loss between the BS and the bins. No SINR calculations are performed and therefore, no bitrates can be calculated. The intention with this model is to demonstrate the path loss improvements that occur when users are higher up in a building. The path loss calculations are performed as in model six. The difference is that only indoor bins are considered and the way the floors are distributed. Instead of giving every bin just one height and performing one simulation, this model runs as many times as the highest building have floors. The first simulation places all users at ground floor giving a floor height gain of 0 dB. Next simulation is performed at the second floor and all buildings that are high enough to have a second floor are considered. This continues up to the highest building in the area. All of these bins and their path loss values are then compared to the corresponding values at ground floor, see figure 3.6.
Chapter 4

Simulations and Results

4.1 Comparison of computational times

The computational times of the calculations were measured using the tic tac MATLAB commando. The simulation times are for 12 separate complete simulations in Astrid, 6 with the 3D model active and 6 without. It also includes time for plotting, but since that is the same for all models, that time does not effect the comparisons. The results are shown in table 4.1. Since the table is based on one simulation of each model, the values can not be considered as absolutely true since there are other factors such as available memory affecting the simulation. However, the absolute value of the time consumption is less important, the real interest is in the comparison between the different models. The comparison shows that the first and second models are the fastest but that the sixth and seventh model are equal in speed. The forth and fifth models are considerably much more computationally demanding, and that is obvious in their processing times. The third model is somewhere in between.

There are also some preparations needed to perform before each model, for example the LOS calculations described in chapter 3. Model one and two need no preparations, model six and seven need one (calculation of LOS and associating bins to buildings which is performed simultaneously) while model three, four and five need another two quite time consuming preparations consisting of path loss predictions at higher levels performed by TCP. All these preparations are only needed to be performed one time. Once they are done, the models can be used as many times as wished.

Table 4.1: The computational times of the different models normalized with respect to DL in model one.

<table>
<thead>
<tr>
<th>Model</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time for DL</td>
<td>1</td>
<td>0.69</td>
<td>3.5</td>
<td>7.4</td>
<td>7.6</td>
<td>0.99</td>
<td>1.1</td>
</tr>
<tr>
<td>Time for UL</td>
<td>1.7</td>
<td>1.3</td>
<td>5.2</td>
<td>11</td>
<td>8.4</td>
<td>1.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Table 4.2: Predictions at different heights.

<table>
<thead>
<tr>
<th>Name of gain matrix of prediction</th>
<th>g</th>
<th>g0</th>
<th>g1</th>
<th>gref</th>
<th>g2</th>
</tr>
</thead>
<tbody>
<tr>
<td>height of mobile antennas in prediction</td>
<td>m</td>
<td>1.5</td>
<td>15</td>
<td>18</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 4.3: Gain matrix difference

<table>
<thead>
<tr>
<th></th>
<th>Total number of bins: 123045</th>
<th>g-g0</th>
<th>g-g1</th>
<th>g-gref</th>
<th>g-g2</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of bins with a positive difference</td>
<td>23 627</td>
<td>23 512</td>
<td>36 074</td>
<td>953</td>
<td></td>
</tr>
<tr>
<td>number of bins with a positive difference</td>
<td>g0-g1</td>
<td>g0-gref</td>
<td>g0-g2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of bins with a positive difference</td>
<td>55 766</td>
<td>65 554</td>
<td>99 784</td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of bins with a positive difference</td>
<td>g1-gref</td>
<td>g1-g2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of bins with a positive difference</td>
<td>73 359</td>
<td>99 869</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of bins with a positive difference</td>
<td>gref-g2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of bins with a positive difference</td>
<td>87 217</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.2 Investigation of the G-Matrix

This investigation aims at investigating the path loss information predicted by TCP. The information is provided in the form of a big matrix containing the path gain predictions between the bins in the considered area and a certain number of BSs with best predicted path gain to the bins in question. In this investigation, the prediction is masked so that the matrix only contains the indoor bins in the restricted area, see figure 3.1 on page 21. This yields 123 045 bins to study. Predictions for mobile antennas at different heights have been compared to investigate whether the assumption of a logarithmic increase in gain with mobile antenna height is correct. The names and heights of the different gain matrices are found in table 4.2. The gain values compared are the values between the bins and their serving BS.

The differences are calculated as the difference between a lower project and a higher. It is expected to be negative since the path gain is supposed to be more negative on the lower levels and slightly less negative on the higher levels. A positive difference means there has been a loss with height instead of a gain. There are a significant number of bins that does not follow the anticipated behavior. The bins with positive differences i.e. an extra loss with height, do not completely coincide between the different projects.

This problem might arise from the tilt of the antennas, that is, the predictions are correct but the assumption that the path loss should decrease logarithmically (in dB) as the heights of the mobile antennas increase is inadequate. To investigate if this is really the case the prediction at 1.5 m called g and the prediction at 15 m called g0 was used for a comparison. The angle in the vertical plane between the MS and their serving BS was calculated for 5 different bins that got positive differences. The angles were then used to count backwards via the vertical lobe patterns and compare the results to the difference found. The result is found in 4.4. It is the same serving BS in all bins and at both heights.
The lobe pattern of the employed antenna can be seen in Figure 4.1.

There is also the issue that the serving BS might have changed between the predictions on the different levels. In Table 4.5 the numbers of bins changing serving BS are shown. However, this is a process that would occur in reality too, so no measures were made to make the same BS be serving at all heights.

Model three, four and five in different ways all use path loss values predicted by TCP in bins found to be in LOS of the BS by Astrid. Therefore, a comparison between the path loss value that was found to be in LOS of the BS through the LOS calculations performed as in Section 3.2.2.3 on page 25 i.e. with outside bins and a theoretical free space propagation path loss (2.4), can be seen in Table 4.6a. There is a also a comparison to a free space propagation with an added approximate vertical lobe pattern loss. In Table 4.6b it is investigated how much the angle between the bin and it’s serving BS affects the loss due to the directional lobe pattern of the antennas. This is done to see if any difference in loss in Table 4.6a could be explained by the vertical lobe patterns, thereby showing that the path loss predictions in TCP correspond to the path loss assumptions made on them.
Table 4.4: Path loss due to vertical angles.

<table>
<thead>
<tr>
<th>height of serving BS [m]</th>
<th>height of MS [m]</th>
<th>vertical angle between BS and MS [deg]</th>
<th>angle in lobe pattern after correction for mechanical downtilt</th>
<th>additional loss due to the lobe pattern [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>15</td>
<td>0.6727</td>
<td>358.6727</td>
<td>(0.5)-1.25</td>
</tr>
<tr>
<td>mechanical downtilt [deg]</td>
<td>15</td>
<td>0.2439</td>
<td>358.2439</td>
<td>(1.25)-2.0</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>0.8658</td>
<td>358.8658</td>
<td>0.5-(1.25)</td>
</tr>
<tr>
<td>electrical downtilt [deg]</td>
<td>1.5</td>
<td>1.4981</td>
<td>359.4981</td>
<td>0.25-(0.5)</td>
</tr>
</tbody>
</table>

(a) Comparison of four different bins with a positive difference g-g0. The two values in the last column corresponds to the loss values at the two nearest half-degrees. The value within parenthesis is the loss value corresponding to the angle the furthest away from the calculated angle in the forth column.

<table>
<thead>
<tr>
<th>Difference in path gain g0-g1 [dB]</th>
<th>Maximal difference in additional loss [dB]</th>
<th>Minimal difference in additional loss [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3900</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0.4000</td>
<td>1.75</td>
<td>0</td>
</tr>
<tr>
<td>0.3800</td>
<td>0.35</td>
<td>-0.05</td>
</tr>
<tr>
<td>0.3900</td>
<td>1.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

(b) Comparison of the loss values rendered by the differences between the different predictions and losses due to vertical beam shaping

Table 4.5: Gain matrix, serving BS difference

<table>
<thead>
<tr>
<th>Total # of bins</th>
<th>g vs g0</th>
<th>g vs g1</th>
<th>g vs gref</th>
<th>g vs g2</th>
</tr>
</thead>
<tbody>
<tr>
<td>123 045</td>
<td>40 212</td>
<td>46 878</td>
<td>68 252</td>
<td>961</td>
</tr>
<tr>
<td># that has changed serving BS</td>
<td>g0 vs g1</td>
<td>g0 vs gref</td>
<td>g0 vs g2</td>
<td></td>
</tr>
<tr>
<td>18 334</td>
<td>55 480</td>
<td>39 707</td>
<td></td>
<td></td>
</tr>
<tr>
<td># that has changed serving BS</td>
<td>g1 vs gref</td>
<td>g1 vs g2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>47 469</td>
<td>46 438</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># that has changed serving BS</td>
<td>gref vs g2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>67 991</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.6: Loss of LOS bins.

(a) Comparison between predicted loss and theoretical free space propagation loss.

<table>
<thead>
<tr>
<th>Number of bins participating in comparison: 3589</th>
<th>loss from TCP (loss1) [dB]</th>
<th>losses from free space calculations (loss2) [dB]</th>
<th>losses from free space calculations (loss3) + added loss from antenna lobe (1dB) [dB]</th>
<th>difference $^1$ between loss1 and loss2 (loss1-loss2) [dB]</th>
<th>difference $^2$ between loss1 and loss3 (loss1-loss3) [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>max</td>
<td>127.2190</td>
<td>113.3136</td>
<td>114.3136</td>
<td>47.1564</td>
<td>48.1564</td>
</tr>
<tr>
<td>min</td>
<td>56.8890</td>
<td>53.6442</td>
<td>54.6442</td>
<td>0.0038</td>
<td>0.0141</td>
</tr>
<tr>
<td>mean</td>
<td>92.3005</td>
<td>84.2029</td>
<td>85.3029</td>
<td>8.0976</td>
<td>7.0976</td>
</tr>
<tr>
<td>median</td>
<td>89.6590</td>
<td>85.2711</td>
<td>86.2711</td>
<td>9.2829</td>
<td>8.2829</td>
</tr>
</tbody>
</table>

(b) Angles between the LOS bins and their serving BSs and the loss that angles give rise to due to the vertical lobe patterns of the antennas.

<table>
<thead>
<tr>
<th></th>
<th>angle between BS and bin [deg]</th>
<th>angle of deviation from maximum of lobe pattern of the antenna in figure 4.1 on page 32 [deg]</th>
<th>corresponds to a loss minus antenna gain due to the lobe pattern of the antenna in figure 4.1 on page 32 [dB]</th>
<th>angle of deviation from maximum of lobe pattern of the antenna in figure 3.5 on page 28 [deg]</th>
<th>corresponds to a loss minus antenna gain due to the lobe pattern of the antenna in figure 3.5 on page 28 [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>max</td>
<td>86.7509</td>
<td>273.2491</td>
<td>9.70 - (9.70)</td>
<td>267.2491</td>
<td>13.70 - (12.75)</td>
</tr>
<tr>
<td>min</td>
<td>81.8152</td>
<td>81.8152</td>
<td>(21.05) - 20.90</td>
<td>75.8152</td>
<td>(20.10) - 20.20</td>
</tr>
<tr>
<td>max (absolute value of angles)</td>
<td>86.7509</td>
<td>273.2491</td>
<td>9.70 - (9.70)</td>
<td>267.2491</td>
<td>13.70 - (12.75)</td>
</tr>
<tr>
<td>min (absolute value of angles)</td>
<td>0.00</td>
<td>0.00</td>
<td>-17.80 (antenna gain)</td>
<td>0.2006</td>
<td>-16.00 - (15.90)</td>
</tr>
<tr>
<td>mean deviation from maximum of antenna lobe</td>
<td>15.0301</td>
<td>344.9699</td>
<td>(3.25) - 2.20</td>
<td>338.9699</td>
<td>(8.70) - 10.10</td>
</tr>
<tr>
<td>median</td>
<td>9.0401</td>
<td>350.9599</td>
<td>(8.95) - 4.40</td>
<td>344.9599</td>
<td>(8.40) - 8.10</td>
</tr>
</tbody>
</table>
Table 4.7: Parameter settings used for simulations.

<table>
<thead>
<tr>
<th>General</th>
<th>Base station</th>
<th>Terminal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>20 MHz</td>
<td>40 W</td>
</tr>
<tr>
<td>Frequency band</td>
<td>2.6 GHz</td>
<td>2.2 dB (UL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 dB (DL)</td>
</tr>
<tr>
<td>Down link</td>
<td>64 QAM,</td>
<td>Up link</td>
</tr>
<tr>
<td>modulation</td>
<td>MIMO</td>
<td>16 QAM,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SIMO</td>
</tr>
</tbody>
</table>

4.3 Models

From every simulation a set of plots are outputted. The set includes plots of cdf for SINR, cdf for path loss distributions, cdf for bitrate distributions, average and worst 10 percentile of mean bitrates in Mbps plotted against the capacity of the system, the average cell load in GB/h for different loads. The average cell load $C_{\text{average}}$ [GB/h] is calculated as shown in equation (4.1)

$$C_{\text{average}} [\text{GB/h}] = \frac{\text{mean} (R) \cdot \text{load} \cdot 3600}{8 \cdot 1000} \quad (4.1)$$

where $R [\text{Mb/s}]$ is the bitrates for all bins and $l [\%]$ is the fractional load. The worst 10% bitrates are calculated in the same way but with the worst 10-percentile of the bitrates instead of the mean of the bitrates. In all the plots it is the difference in bitrates arising from the 3D models with gain for higher bins relative the two dimensional [2D] models where all the bins are on the ground floor that is important. The absolute values that of course is highly dependant on the used radio access technique, in this case LTE, is less important, however, the parameters applied can be seen in table 4.7.

The green 2D curves present in all plots are meant to be a reference, so they are constant and does not vary between the different models. The exception is in the results in 4.3.2.6 on page 49 where an additional 2D curve is present that is not identical to the other models’.

4.3.1 Without LOS Considerations

4.3.1.1 Results from the First Model

The employment of the 3 dB/floor height gain model results in significant improvement of indoor path loss distribution, see figure 4.2. The improvements seem to be distributed evenly over all bins, i.e. the 3D path loss curve follows the 2D curve on almost equal distance all the way. The SINR is also improved, both in DL and UL. In figure 4.3 the SINR for a system with 30% load is shown. Especially the bins with poorest SINR in the UL are improved. This improvement renders higher bitrates, both average and the worst 10%, see figure 4.4. The difference in absolute bitrate values decreases with increasing traffic.
Figure 4.2: Path loss predictions with first model in indoor bins.

Figure 4.3: SINR in DL (to the left) and UL in first model.

load in the cell as expected, however the difference expressed as a percentage is still significant and the capacity, the average cell load is still increased.

4.3.1.2 Results from the Second Model

This model using 3 dB/floor height gain up to the highest floor of the building, gives an even more optimistic result than the first model. This is evident in figure 4.5 showing path loss for indoor bins, figure 4.6 showing the SINR in DL and UL and consequently also in figure 4.7 showing the mean bitrates and capacity. The general behavior of the improvements are the same as in the first model, which is expected considering how similar the models are. However, the average height of the buildings in the city considered is 22.12 m and the median height is 21.00 m which corresponds to 7.42 floors and 7.00 floors respectively. That means that more than half of the indoor bins are given floors higher than the maxfloor in the first model, a maxfloor that the floor height gain of 3 dB/floor is adapted to [7].
(a) Average (to the left) and the worst 10 percentile bitrates at different loads in the DL of model one.

(b) Average (to the left) and the worst 10 percentile bitrates at different loads in the UL of model one.

Figure 4.4: Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.

Figure 4.5: Path loss predictions with second model in indoor bins.
Figure 4.6: SINR in DL (to the left) and UL in second model.

(a) Average (to the left) and the worst 10 percentile bitrates at different loads in the DL of model two.

(b) Average (to the left) and the worst 10 percentile bitrates at different loads in the UL of model two.

Figure 4.7: Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.
4.3.2 Models With LOS Considerations

4.3.2.1 Results from the Third Model

The results of this the first model with LOS considerations using the interpo-
lations from TCP are quite similar to the results of the previous two models
in that the indoor path loss curve for the 3D model approximately follows the
2D model. The decrease in path loss shown in figure 4.8 is however less for the
bins with lower path loss than for the bins with higher path loss. The SINR
at 30 % load in the UL is also different from the previous models in that the
3D model’s curve intersects the 2D model’s rendering the difference in SINR
negative for the bins with the best SINR, see figure 4.9. The results of this can
be seen in how the bitrates in the UL are affected. As seen in figure 4.10 the
average bitrates and the capacity in the UL decreases below the bitrate of the
2D model when the load increases from 70 % to 99 %.
[a] Average (to the left) and the worst 10 percentile bitrates at different loads in the DL of model three.

[b] Average (to the left) and the worst 10 percentile bitrates at different loads in the UL of model three.

Figure 4.10: Mean bitrates at 7 different loads: 5%, 10%, 20%, 30%, 50%, 70% and 99%. The highest bitrate corresponds to the lowest load and vice versa.
Figure 4.11: Path loss predictions with fourth model in indoor bins.

Figure 4.12: SINR in DL (to the left) and UL in fourth model.

4.3.2.2 Results from the Fourth Model

The simulations performed using the fourth model with indoor loss calculations, results in an indoor path loss curve that looks very different from all three previous models. As seen in figure 4.11, the 3D curve and the 2D curve intersects and the highest path loss is increased in the 3D model. This means that some bins get a negative floor height gain, a loss. The SINR in the DL seen in figure 4.12 is quite unaffected in that the 3D model still improves on the 2D model. The improvement is less than in other 3D models. The UL SINR at 30 % load is affected in that the 3D curve now intersects the 2D curve in two places\(^3\) meaning that the worst SINR is worse and the best SINR is also worse. The average SINR is better.

The bitrates shown in figure 4.13 are significantly different from previous results. The DL bitrates are indeed higher for lower loads, but at high loads the bitrates and the capacity, or average cell load, decrease to be lower than the values in the 2D model. The same can be found in the UL but only for the

\(^3\)They actually intersect at more places but there are two major trends.
(a) Average (to the left) and the worst 10 percentile bitrates at different loads in the DL of model four.

(b) Average (to the left) and the worst 10 percentile bitrates at different loads in the UL of model four.

Figure 4.13: Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.
average bitrates. The worst 10 percentile are still improved in bitrates compared to the 2D model for all loads. The capacity however decreases for the really high loads.

4.3.2.3 Results from the Fifth Model

The path loss curve resulting from the fifth model using outdoor bins for LOS considerations and indoor path loss calculations, intersects the curve from the 2D model as seen in figure 4.14 just like the path loss curve resulting from model four. However, the number of bins with a negative height gain, or loss is smaller in model five than in model four. The SINR curves when the system is loaded to 30% show, in figure 4.15, the poorest values in the DL decreasing with respect to the 2D model. The UL SINR is as always more complex but it also shows a decrease with respect to the 2D model in SINR for the poorest value. In addition also the best SINR values are decreased compared to the 2D model but the average SINR values are increased. The bitrates in figure 4.16 show nice increases compared to the 2D models bitrates for both DL and UL. The capacity is not improving as much but it is never lower than that of the 2D model. The higher the load, the smaller the increase in bitrates and capacity.

Results from the Fifth Model with Lower Wall Loss Constants

The results from this model which is basically the same as the fifth model but has a lower wall loss constant added, see section 3.2.2.3 on page 25, are of course quite similar to the results of the fifth model. The differences are better path loss results, 4.17, better SINR curves 4.18 and higher bitrates and capacity 4.19.

4.3.2.4 Results from the Sixth Model

There results from the sixth model with building specific path loss curves shows a path loss curve that improves on the 2D model for all bins. The improvement is slightly larger for the higher path loss values as seen in figure 4.20. The SINR
Figure 4.15: SINR in DL (to the left) and UL in fifth model.

(a) Average (to the left) and the worst 10 percentile bitrates at different loads in the DL of model five.

(b) Average (to the left) and the worst 10 percentile bitrates at different loads in the UL of model five.

Figure 4.16: Mean bitrates at 7 different loads: 5%, 10%, 20%, 30%, 50%, 70% and 99%. The highest bitrate corresponds to the lowest load and vice versa.
Figure 4.17: Path loss predictions with fifth model with lower wall loss constants in indoor bins.

Figure 4.18: SINR in DL (to the left) and UL in fifth model with lower wall loss constants.
(a) Average (to the left) and the worst 10 percentile bitrates at different loads in the DL of model five with lower wall loss constants.

(b) Average (to the left) and the worst 10 percentile bitrates at different loads in the UL of model five with lower wall loss constants.

Figure 4.19: Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.
also shows improvements towards the 2D model for all bins, at least in the DL at 30% load. The UL SINR is poorer for the high SINR values but improves on the low values, see figure 4.21. This means that the DL bitrates and capacity shown in figure 4.22 also are improvements compared to the 2D model. The UL average bitrates and capacity decreases to be lower than the 2D models values, when the load increases from 50% to 70%. The worst 10 percentile bitrates in the UL improves on the 2D model for all loads and compared to the fifth model, the improvement is larger but the capacity decreases for higher loads.

4.3.2.5 Results from the Seventh Model

The results from the simulations performed with the seventh model are quite similar to the results of the sixth model since apart from the constant distributions and vertical lobe patterns they are identical. The path loss curve found in figure 4.23 shows an decrease in path loss for all bins compared to the 2D model even though the gain is not as large as in the sixth model. The SINR curves from when the system is loaded to 30% shown in figure 4.24 also show the same behavior as model six with improvements for all bins in the DL and
Figure 4.22: Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.
improvements for all bins except the better part in the UL. The consequences of this can be seen in figure 4.25 where the worst 10 percentile bitrates in the both the DL and the UL are improved compared to the 2D model for all loads even if the capacity is not improved for higher loads in the UL. The average bitrates and capacity are improved compared to the 2D model for all loads in the DL but not in the UL. The UL average bitrates and capacity instead deteriorate compared to the 2D model for loads higher than 50%.

4.3.2.6 Results from Crowded 3D Model Using Model Six

The results of the crowded 3D model described in section 3.2.2.6 on page 29 show a large decrease in the predicted path loss. The blue curve in figure 4.26 is the crowded 3D model with all bins represented on all the floors and the red curve are the corresponding bins but only on the ground floor. The green curve is the usual 2D model’s path loss curve. The improvement of the 3D model on the 2D model is very significant, especially for the path loss that is already low. The red curve also improves on the ordinary 2D model, meaning that it is the bins with the best SINRs that becomes represented multiple times when the red
(a) Average (to the left) and the worst 10 percentile bitrates at different loads in the DL of model seven.

(b) Average (to the left) and the worst 10 percentile bitrates at different loads in the UL of model seven.

Figure 4.25: Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.
Figure 4.26: Path loss in indoor bins. In the blue curve, every floor in every building is represented once with the corresponding gain according to model six. The red curve contains equally many values but only from the corresponding ground floors. The green curve is the usual ground floor path loss with every building counted once.

curve is created.

4.3.3 All models in the same plots

4.3.3.1 Path loss

The cdfs for the path loss predicted by all the different 3D models and the 2D model for the indoor bins are represented in figure 4.27. Figure 4.27b shows the middle of the total cdfs and there all 3D models in fact improve on the 2D model. Figure 4.27c shows to top of the cdfs and the highest path losses and it is clear that the path losses predicted by model four and five are inferior to the path loss predicted by the 2D model. The model predicting the best path losses are the second model, followed by the first. The third, sixth, seventh and fifth with lower wall loss constants are all close to each other and the fourth predicts the least improvements in path loss.

4.3.3.2 SINR

In figure 4.28 the SINR curves for 30 % load predicted by all the different 3D models and the 2D models are shown. The DL SINR curves are all very close,
Figure 4.27: Path loss in indoor bins. All 3D models tested via Astrid are represented. Note the black dotted line that represents a 2D simulation, i.e. a simulation without a height distribution for bins.
but the best SINRs are predicted by the second model and the worst by the fifth model. The UL have a little more variation and it is the fourth model that predicts the worst SINR and the second that predicts the best. In between the other models are entwined and vary along the stretch of the curve.

4.3.3.3 Mean Bitrates and Capacity

The figure 4.29 on page 55 shows the bitrates and capacity of all the models. All of the models show similar behavior even if the level of improvements vary between them. The biggest improvements for all models are found in the worst 10 percentile. The gain in percent in bitrates are over all larger in the UL than in the DL. The second model shows the largest improvements in both UL and DL. The least improvements are given by model four in the DL and model six and seven in the UL.
Figure 4.28: SINR for all bins at 30% load. All tested models are represented. Note the black dotted line that represents a 2D simulation, i.e. a simulation without a height distribution of bins.
Figure 4.29: Mean bitrates and capacity of all models.
Chapter 5

Discussion and Conclusions

5.1 Discussion and Conclusions

Through the comparison of computational times performed in section 4.1 it is found that the fourth and fifth model and to a certain degree also the third are much more time consuming and require more preparation than the first, second, sixth and seventh models. It implies that if the results of the models are at least equally trustworthy, one of the latter should be used.

As seen in table 4.3 on page 31 the path gain predictions performed by TCP at different levels does not increase from the lower levels to the higher levels for all bins. The closer the predictions are in height, the more bins have instead worse path gain at the higher level than at the lower. One possible explanation for this is that the vertical lobe patterns of the antennas in the BS are tilted downwards, rendering the path gain worse at higher levels. In table 4.4 on page 33 four bins with a negative gain are investigated with respect to the angle between the bins and the serving BS and the loss this might give rise to due to the lobe pattern. It is found that in three of the four cases investigated, the additional loss might be totally explained by the lobe pattern. One case does not allow the lobe pattern to explain its loss value completely. Most BSs have a very narrow vertical lobe pattern and this kind of phenomena can thus be expected at higher floors. That might imply that the path loss relationship between higher and lower predictions might not be as simple as assumed in the interpolations.

In table 4.6 on page 34 a comparison between the path loss value predicted by TCP to bins found to be in LOS by the calculations in 3.2.2.3 on page 25, and the free space propagation path loss predictions. As seen, they differ with several dB and even if the table 4.6b on page 34 explains some of the additional losses with antenna lobe patterns, there are again some losses that can not completely be accounted. These might arise from multiple knife edge effects. As described in section 2.1.3 on page 9 the knife edge effect affects the propagation
of a wave even if the obstructing object is not disturbing the LOS, as long as it is close enough. And should many such obstructing but not LOS disturbing objects be situated between the BS and the bin, the path loss could be expected to be several dB higher than the free space propagation path loss.

The first model does not make use of all the data available which makes it less detailed than necessary. The results obtained from it can still be used as some kind of a reference to the other models, if they seem to behave in an expected and reasonable way even if the deterministic value of the model is somewhat diminished as it uses the average building height and does not consider the LOS factor.

The second model is more detailed and could therefore be considered to be more accurate. Unfortunately, the empirically derived model that it is based on, does not support buildings that are higher than 6 floors, meaning that results of this model is actually less trustworthy than the first model. It is reasonable to assume that it is actually incorrect to let the floor height gain be constant for higher floors, since the vertical lobe patterns of the BS are often quite narrow and downtilted, see for example figure 4.1 on page 32. In addition, the heights of the buildings are in some cases more than four times higher than the average BS height. Another reason to suspect that model two is unrealistically optimistic in its predictions is the impact of LOS. Once a building is high enough to achieve a LOS connection to the BS serving the users in the building, the floor height gain stops [9]. This is because LOS means that the best possible propagation condition is achieved and there is no further gain to win from being on a higher floor.

The third model accounts for the influence of LOS. The issue with this model is that it uses the indoor values from TCP which are calculated as described in (2.28) on page 18. Those values are calculated without a direct dependence on the LOS considerations even if a comparison is performed to ensure that the predicted path loss value is not too low, see section 2.2.5.1 on page 18. This circumstance causes that it is not sure if it is the bin that would actually give the best indoor value that is actually chosen for indoor value calculations since these calculations takes place at the ground floor and the LOS is normally found on higher floors. In addition, it also means that if there are one or more LOS bins on a floor which triggers the inside bins to get their path loss value from the interpolated TCP, that does not mean that the values given to the inside bin has anything to do with the path loss value of the bin that has been found to have LOS at a certain height. In figure 5.1, the yellow bins illustrate the LOS bin and the surrounding bins giving it its path loss value and the lilac bins illustrate the inside bin given a value from the TCP interpolations because of the yellow LOS bin, but whose path loss value is not affected by the LOS bin at all. In fact, none of the bins given as a choice for the path loss value of the inside bin is even on the same side of the building as the LOS bin, meaning that they probably doesn’t experience LOS. This means that even if the path loss curve of the third model is rather similar to the curve of the first model, there are some
logical errors in the way it is created and therefore it is not as trustworthy. It can also be seen in figure 4.27a on page 52 that the path loss curve of the third model improves the path loss on the 2D model the least in the 10 percentile as opposed to model one and two that improve the least in the 90 percentile.

To avoid the problem with the indoor calculations of the third model and avoid the indoor bin top get a value that has nothing to do with the path loss value of the bin found to be in LOS, the fourth model instead use an indoor loss slope to calculate the value of the indoor bins on the same floor of a LOS bin. However, since the LOS bins are still found amongst the indoor bins, the trouble with the indoor calculations does not disappear. As illustrated in figure 5.2 it might actually in unlucky cases increase the problems instead by forcing the calculations to be performed in a criss cross way thus increasing the path loss. The effect is clearly seen in figure 4.11 on page 41 where the odf shows a large increase in path loss.

The fifth model therefore uses outdoor bins for LOS calculations instead and adds its own outdoor-to-indoor or wall losses. This clearly improves the results, especially when the lower grazing angle loss constant is used. This lower constant is realistic since it can be considered as an average grazing angle loss. In addition it makes the total wall loss constant in model five match the outdoor-to-indoor loss $L_{LOS}$ of model six. Since that value of model six is found through measurements it is reasonable to believe it is fairly accurate. However, it should be remembered that $L_{LOS}$ is a value meant to be related to the free space propagation path loss value outside. And as seen in table 4.6 on page 34 the loss values of TCP are not really the same as the free space propagation values, but
higher. This might explain the intersection between the path loss curve of the 2D model and the fifth models. Comparing model three with model four and five also gives a hint on the values from TCP not being suitable to use in the manner they are used in model four and five where the bins used to calculate indoor losses are fixed in Astrid and not chosen by TCP. There seems to be a problem when an exterior operator tries to control from what bin a calculation should be made.

The sixth model leaves the attempts to use the finding of bins with LOS for creating a path loss slope to go inside the building. Instead it uses the LOS information for adapting the floor height gain to each building's special circumstances. The included $L_{f_{sp}}$ calculations, which are described in section 2.2.4 on page 15 and are dependent on the distance between the BS and the bin, make the model account for the fact that really high buildings will be negatively affected by their height, possibly due to the properties of the employed antennas. Another difference between this model and model four and five is that in order to calculate the gain, the same floor height gain model is used at ground floor and the floor given to the bin and then the difference is added to the predictions performed by TCP. The fourth and fifth model instead calculates a gain that is a comparison between the models path loss calculations and the calculations performed by TCP. It is natural that this causes some disturbance in the results, and indeed, the fourth and fifth model are the only models to show the behavior of the path loss curves intersecting with that of the 2D model giving rise to the suspicion that this intersection is not a realistic behavior.

The sixth model does not take the vertical lobe patterns into consideration.
and therefore the seventh model was created. As expected this decreases the path loss improvements but at the same time it makes the model more realistic since the measurements in [11] which [9] is based on, are performed with a non-directive antenna. In addition to the vertical lobe patterns, the seventh model also introduces Gaussian distribution functions for the floor height gain constant and the building penetration loss. Exactly how this effects the model is hard to say since it is not the only difference between the sixth and the seventh model, but it is a more realistic way to portrait building penetration loss and height gain.

The crowded 3D model using model six that gives very positive improvements in the path loss results would probably be poorer in the SINR results due to the closeness of the users. However no such simulations were performed, and so nothing precise can be said about it at this point. The SINR is generally improved in both DL and UL. There is thus a greater gain in signal strength than in interference when a UE is situated on a higher floor than ground floor. It could be questioned how this would be if a slightly denser and perhaps not uniform UE distribution would be introduced. The simulations show that the bitrate and capacity in the UL and the DL are not equally sensitive to interference. This is visible in the plots of the average and worst 10 percentile of mean bitrates plotted against the capacity of the system for different loads. In the DL it is only the forth models curves that does not always exceed the 2D model in capacity. The UL on the other hand has this behavior for almost all models at higher loads.

All in all, considering both the accuracy and the computational speed of the models, the seventh model is recommended for normal use even if it might be interesting to test the other models to get a sense of the span of results that might be expected.

5.2 Continuation

An investigation of the influence of the vertical lobe patterns on the sixth model without the added Gaussian distribution from model seven would be interesting and enable some conclusions of the effect of lobe pattern losses.

It would be interesting to see how changing the distribution of floor height gain and building penetration loss constants in model seven from Gaussian to every bin to Gaussian to every building, would impact the result.

An SINR investigation of the crowded 3D model using model six would be interesting since it would introduce a much more dense user equipment distribution.

In the simulations performed for this report, only one type of resource sharing has been used, see section 3.1 on page 20. Other types and their effects on the capacity of the system needs further investigation.

All simulations in this report are performed in macrocells where the BS are
generally placed above the average building heights. If instead microcells would be used, with lower BSs, or a heterogeneous network with both macro and micro it is likely that the height gain would be affected. In what way and how much is a question that would require a much deeper investigation, possibly starting with the performance of measurements in such environments.
Bibliography


Nomenclature

2D  Two dimensional
3D  Three dimensional
BS  Base station
cdf Commulative distribution function
DL  Down link, transmission from BS to UE.
LOS Line of sight
MS  Mobile station
NLOS None line of sight
SINR Signal to interference and noise ratio
TCP TEMS Cellplanner. Recently changed to MENTUM CellPlaner for new releases of the program.
UE  User equipment
UL  Up link, transmission from UE to BS.
List of Figures

1.1 Plausible scenarios? ............................................. 5

2.1 The reflected and transmitted component of a wave incident on an interface. θi,1,t are the angles between the normal of the interface and the different rays and n1,2 are the refractive indexes of the different materials. ............................................. 8

2.2 Scattering from a rough surface. The black ray is the incoming ray and the gray rays are the less energetic scattered rays. ........ 9

2.3 Diffraction of energy from a wavefront as it impinges on an obstacle. The gray circles symbolizes the imaginary wavefronts of the point sources. The wavefront thus curves around the corner. 10

2.4 Geometry of knife edge diffraction. ............................. 10

2.5 Definition of angles and distances. The building is seen from above. 13

2.6 Definition of outdoor pixels. Only Pk,2–6 is outdoor. ........ 14

2.7 Average building penetration loss, using GFL = 3.0 dB, nFB = 7, a = 4 and LLOS = 24.5 dB. ................................. 16

2.8 Indoor bin and the four surrounding outdoor bins considered as starting positions for indoor propagation. .................... 19

3.1 Analysis area ..................................................... 21

3.2 Floor distribution. In the first model the height of all buildings is 6 floors. In all other models the height of the buildings varies according to the building data. ................................. 23

3.3 LOS calculations. The green and red lines are the imaginary lines draw between the BS and two consecutive floors, the lower without LOS and the higher with LOS. ......................... 24

3.4 Cdf of building penetration loss LLOS (to the left) and floor height gainGFL. ............................................. 27

3.5 The vertical lobe pattern used to represent all BS in model seven. The antenna gain is 16.0 dBi. ................................. 28

3.6 Floor distribution in the crowded 3D model. The path loss at ground floor in building A, B and C will be counted 8, 4 and 6 times respectively, to create a data series for the ground floor predictions comparable to the higher level predictions that will be performed once for every floor in a building. ............. 29

64
4.1 Vertical lobe pattern of serving BS antenna. The antenna gain is 17.8 dBi.

4.2 Path loss predictions with first model in indoor bins.

4.3 SINR in DL (to the left) and UL in first model.

4.4 Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.

4.5 Path loss predictions with second model in indoor bins.

4.6 SINR in DL (to the left) and UL in second model.

4.7 Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.

4.8 Path loss predictions with third model in indoor bins.

4.9 SINR in DL (to the left) and UL in third model.

4.10 Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.

4.11 Path loss predictions with fourth model in indoor bins.

4.12 SINR in DL (to the left) and UL in fourth model.

4.13 Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.

4.14 Path loss predictions with fifth model in indoor bins.

4.15 SINR in DL (to the left) and UL in fifth model.

4.16 Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.

4.17 Path loss predictions with fifth model with lower wall loss constants in indoor bins.

4.18 SINR in DL (to the left) and UL in fifth model with lower wall loss constants.

4.19 Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.

4.20 Path loss predictions with sixth model in indoor bins.

4.21 SINR in DL (to the left) and UL in sixth model.

4.22 Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.

4.23 Path loss predictions with seventh model in indoor bins.

4.24 SINR in DL and UL in seventh model.

4.25 Mean bitrates at 7 different loads: 5 %, 10 %, 20 %, 30 %, 50 %, 70 % and 99 %. The highest bitrate corresponds to the lowest load and vice versa.
4.26 Path loss in indoor bins. In the blue curve, every floor in every building is represented once with the corresponding gain according to model six. The red curve contains equally many values but only from the corresponding ground floors. The green curve is the usual ground floor path loss with every building counted once.  

4.27 Path loss in indoor bins. All 3D models tested via Astrid are represented. Note the black dotted line that represents a 2D simulation, i.e. a simulation without a height distribution for bins.  

4.28 SINR for all bins at 30\% load. All tested models are represented. Note the black dotted line that represents a 2D simulation, i.e. a simulation without a height distribution of bins.  

4.29 Mean bitrates and capacity of all models.  

5.1 Indoor calculations in model three.  

5.2 Indoor calculations in model four.
List of Tables

3.1 Building height distributions ................................. 25

4.1 The computational times of the different models normalized with respect to DL in model one ................................. 30
4.2 Predictions at different heights ............................... 31
4.3 Gain matrix difference ........................................ 31
4.4 Path loss due to vertical angles ............................... 33
4.5 Gain matrix, serving BS difference ........................... 33
4.6 Loss of LOS bins ............................................. 34
4.7 Parameter settings used for simulations ........................ 35
Appendix A

All Plots

A.1 First Model

A.1.1 Mean Bitrates and Capacity

Mean bitrates in DL first model

Mean bitrates in UL first model
### A.1.2 SINR

Model one DL SINR

Model one UL SINR

### A.1.3 Path Loss

Model one DL and UL path losses. To the left path loss for all bins and to the right path loss for indoor bins.
A.2 Second Model

A.2.1 Mean Bitrates and Capacity

Mean bitrates in DL second model

Mean bitrates in UL second model

A.2.2 SINR

Model two DL SINR
Model two UL SINR

A.2.3 Path Loss

Model two DL and UL path losses. To the left path loss for all bins and to the right path loss for indoor bins.
A.3 Third Model

A.3.1 Mean Bitrates and Capacity

Mean bitrates in DL third model

Mean bitrates in UL third model

A.3.2 SINR

Model three DL SINR
Model three UL SINR

### A.3.3 Path Loss

Model three DL and UL path losses. To the left path loss for all bins and to the right path loss for indoor bins.
A.4 Fourth Model

A.4.1 Mean Bitrates and Capacity

Mean bitrates in DL fourth model

Mean bitrates in UL fourth model

A.4.2 SINR

Model four DL SINR
Model four UL SINR

A.4.3 Path Loss

Model four DL and UL path losses. To the left path loss for all bins and to the right path loss for indoor bins.
A.5 Fifth Model

A.5.1 Mean Bitrates and Capacity

Mean bitrates in DL fifth model

Mean bitrates in UL fifth model

A.5.2 SINR

Model five DL SINR
Model five UL SINR

### A.5.3 Path Loss

Model five DL and UL path losses. To the left path loss for all bins and to the right path loss for indoor bins.
A.6 Fifth Model with Lower Wall Loss Constants

A.6.1 Mean Bitrates and Capacity

Mean bitrates in DL fifth model with lower wall loss constants

Mean bitrates in UL fifth model with lower wall loss constants

A.6.2 SINR

Model five with lower wall loss constants DL SINR
Model five with lower wall loss constants UL SINR

A.6.3 Path Loss

Model five with lower wall loss constants DL and UL path losses. To the left path loss for all bins and to the right path loss for indoor bins.
A.7 Sixth Model

A.7.1 Mean Bitrates and Capacity

\begin{align*}
\text{Mean bitrates in DL sixth model} \\
\text{Mean bitrates in UL sixth model}
\end{align*}

A.7.2 SINR

\begin{align*}
\text{Model six DL SINR}
\end{align*}
A.7.3 Path Loss

Model six DL and UL path losses. To the left path loss for all bins and to the right path loss for indoor bins.
A.8 Seventh Model

A.8.1 Mean Bitrates and Capacity

Mean bitrates in DL seventh model

Mean bitrates in UL seventh model

A.8.2 SINR

Model seven DL SINR
Model seven UL SINR

A.8.3 Path Loss

Model seven DL and UL path losses. To the left path loss for all bins and to the right path loss for indoor bins.