Small-Cell LTE Networks: Evaluating RF Planning Methods

Inês Gonçalves
ines.m.goncalves@ist.utl.pt

Instituto Superior Técnico, Lisboa, Portugal

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Abstract

This work focuses on the study and evaluation of different propagation models and geographical databases used in the planning of LTE networks. A key aspect of the study includes the comparison of the distinct types of databases used: 2D, 2.5D and 3D. Two separate studies were performed: a coverage by area and a point-to-point. The coverage by area analysis used a buffer area, which recreated the path followed in the walk test, to simulate the RSRP and RSRQ levels obtained with each model. The point-to-point study used the location of the walk test samples to obtain the equivalent predicted values. The models simulated are Okumura-Hata, COST 231-Hata, SPM and WinProp UDP. A detailed analysis of the simulations and their comparison to the results obtained during the walk test led to several conclusions. Although the Okumura-Hata model obtained the lowest mean absolute error, it was the WinProp UDP Outdoor model that overall showed the best performance regardless of the analysis method. SPM 2D was the model that adapted better when the walk test samples had a RSRP level higher than -85 dBm while COST 231-Hata obtained the best results in the opposite scenario. A relevant conclusion stresses the importance of accurate drive tests and their validity, as well as the clear improvement obtained in network planning when using dominant path models.
Keywords: LTE, Propagation Models, Walk Test, Clutter Classes, Ray-Tracing

1. Introduction

Over the last decades, fuelled by our need to communicate and the technological advances, there has been a dramatic change in the way we communicate that in time altered consumers needs.

In the beginning of digital cellular networks the technologies developed, like the Global System for Mobile Communications (GSM), were designed to primarily focus on voice traffic. The introduction of 3rd Generation (3G) networks, such as the Universal Mobile Telecommunications System (UMTS), instigated an increased use of data by enabling the use of various services like the Global Positioning System (GPS), mobile television and video conferencing. But in order to respond to those ever-changing needs, the Long Term Evolution (LTE), commonly known as 4th Generation (4G), was created. It was the first cellular communication system designed specifically to support packet-switched data services since the beginning. It aims to provide higher data rates, lower latency and better spectral efficiency.

Still, tendencies have shown an immeasurable growth of data traffic that clearly dominates in comparison to voice traffic. Although 4G connections represented only 26% of mobile connections in 2016, they already accounted for 69% of mobile data traffic, while 3G connections represented 33% of all mobile connections but only 24% of the traffic. According to predictions from [1], by 2021, 4G is expected to correspond to 53% of all connections and 79% of the total traffic. As the capacity demand in mobile networks increased, the development of new wireless communication technologies that solved some of the existing constraints related to radio spectral resources became crucial. Small-cells were presented as a promising solution to increase the capacity and coverage of the network by offloading the macro layer and increasing the Quality of Service (QoS).

One of the tools that contributes to an efficient planning is the use of the correct propagation model for the area in question and the geographical database used alongside it. In this thesis different propagation models, used in the planning and deployment of small-cells in a typical urban scenario, will be analysed. The objective is to compare real data obtained in a walk test with predictions of different propagation models and geographical databases, in a LTE network using a radio network planning software. This thesis was developed in collaboration with Nokia Portugal. This partnership was essential, as it allowed for a realistic study using data obtained in an actual project.

2. Fundamental Concepts

This section provides an overview of the technologies referred to in this thesis such as LTE, small-cells and the different types of propagation models and geographical databases.

2.1. LTE

LTE is a wireless communication standard developed by the 3rd Generation Partnership Project (3GPP), aimed at enhancing the Universal Terrestrial Radio Access Network (UTRAN) and optimizing the radio access architecture. Some of the driving forces for the development of LTE include the increased capability of existing wireline technologies, the need for additional wireless capacity, as well as the need for lower cost wireless data delivery and the existing competition with other wireless technologies. LTE was designed to support only packet-switched services, in contrast to the circuit-switched data services of the previous generations. Its objective is to provide continuous IP connectivity between the user equipment (UE) and the packet data network (PDN) without disruptions during mobility.

The main requirements for this standard included high spectral efficiency, high peak data rates, short round trip time as well as flexibility in frequency and bandwidth. LTE should be able to provide peak user throughput with a minimum of 100 Mbit/s in the DL and 50 Mbit/s in the UL. LTE systems contain two separate categories: the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and the Evolved Packet Core (EPC), as represented in Figure 1.

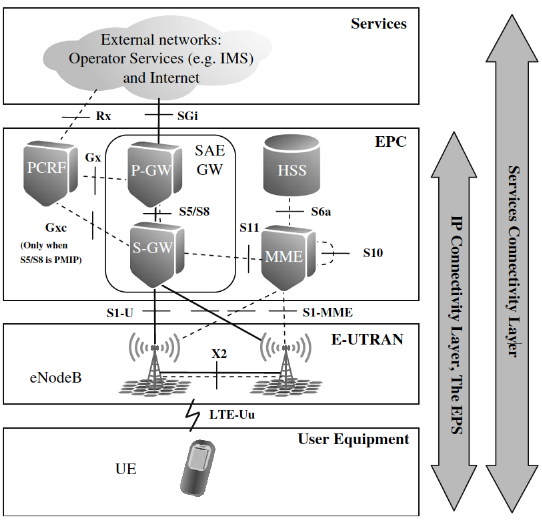

Figure 1: EPS Architecture (extracted from [3]).

The E-UTRAN is a network composed by one type of node - evolved Node B (eNB). These eNBs can cover one or more cells and are capable of handling all the radio related protocols. The eNBs are linked to each other through a X2 interface and connected to the EPC through the S1 interface. The EPC is responsible for the overall control of the UE and establishment of the bearers. A bearer is an IP packet flow with a defined QoS between the gateway and the UE. The main logical nodes of the EPC are the PDN Gateway (P-GW), the Serving Gateway (S-GW) and the Mobility Management Entity (MME).

The multiple access in LTE is based on Orthogonal Frequency Division Multiple Access (OFDMA) for the DL and on Single Carrier Frequency Division Multiple Access (SC-FDMA) for the UL, both with Cyclic Prefix (CP). The transmission in OFDMA is based on the use of narrow, mutually orthogonal sub-carriers. In LTE, each sub-carrier is spaced 15 kHz regardless of the total transmission bandwidth. At the sampling instant of a single sub-carrier, all the others have zero value. The orthogonality achieved by the sub-carrier allows for a more efficient use of the spectrum, because a band guard is no longer needed to avoid sub-carrier interference. One of the main challenges in OFDMA is the high Peak-to-Average Ratio (PAR) of the transmitted signal. This not only limits the transmitted power and reduces coverage but forces the use of better power amplifiers. The UL signal is generated by the users mobile terminal so in this scenario a multiple access technique that enables better power-amplifier efficiency is needed. This was solved by choosing the SC-FDMA in the UL. Similarly to OFDMA, SC-FDMA divides the transmission bandwidth into multiple parallel subcarriers maintaining the orthogonality of the subcarriers. However, in SC-FDMA the data symbols are not directly assigned to each subcarrier independently like in OFDMA. Instead, the signal which is assigned to each subcarrier is a linear combination of all modulated data symbols transmitted at the same time instant. [2]

A high degree of spectrum flexibility is one of the main characteristics of the LTE radio access. LTE supports two types of duplexing: Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) although FDD is the most adopted technique. In TDD, the DL and UL use the same frequency but transmission takes place in different, non-overlapping time slots. Contrarily, FDD implies that DL and UL transmissions take place in different, sufficiently separated, frequency bands but simultaneously.

LTE uses 3 types of Quadrature Amplitude Modulation (QAM). They are the Quadrature Phase Shift Keying (QPSK) or 4-QAM, 16-QAM and 64-QAM modulation schemes. The QPSK carries 2 bits per symbol while 16-QAM and 64-QAM carry 4 and

6 bits per modulation symbol, respectively. These modulation schemes are available in both UL and DL directions in all devices, except for 64-QAM in the UL which depends on the UE capability. The QPSK is the most robust to interference and bad channel conditions, but consequently offers the lower bit rate. In contrast, the 64-QAM allows the higher bit rates in LTE, but requires the best conditions in terms of Signal-to-Interference-plus-Noise Ratio (SINR), by being the most liable to errors due to interference.

2.2. Small-Cells

The unmeasured usage growth of cellphones, tablets and data-hungry applications has caused an exponential growth of traffic in mobile networks, as stated before. Operators have met this challenge by increasing capacity with new radio spectrum, adding multi-antenna techniques and implementing more efficient modulation and coding schemes. However, these measures alone are insufficient in extremely crowded environments and at cell edges where performance can significantly degrade. Complementing macro networks with small-cells is an effective way to extend coverage and increase capacity indoors and outdoors, in public spaces, offices or residences.

Small-cells are operator-controlled, low-powered radio access nodes, used to complement mobile services that is served by macro cells. They are primarily deployed to increase capacity in hot spots with high user demand and to fill in areas not covered by the macro network both outdoors and indoors. Small-cells also improve network performance and service quality by offloading from the large macro cells. A combination of macro cells and small-cells is usually called as a Heterogeneous Network that provides increased bitrates per unit area. There are different types of small-cells which can be grouped according to cell size: femtocells, picocells and microcells, as represented in Figure 2.

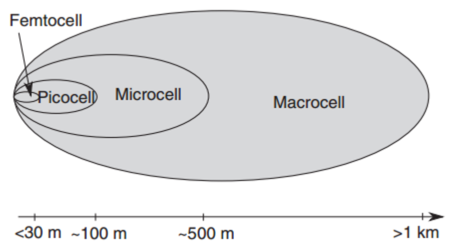

Figure 2: Cell Sizes of Different Technologies (extracted from [6]).

Operators began to install smaller outdoor base stations called microcells as new data services that required higher coverage, emerged. These are deployed in specific areas in which extra capacity is known to be needed, for example near a train station or in a city centre. They are also often temporarily deployed during special occasions like sporting events. Adding microcells in the urban environment allows the operator to subdivide the cells, leading to an optimization of the use of the spectrum and ensuring a better capacity. Microcells have a range of a few hundred metres.

Picocells are small base stations that work very similarly to an Access Point (AP). Picocells have a low power radiating antenna that connects to the operator's core network. Picocells can be used in business environments, shopping centres and airports, for example. They are also useful in high-rise buildings, where the macro cell signal strength decreases with height. The main advantage is that they are considerably cheaper and since they are placed indoor, they effectively increase indoor radio coverage and capacity. These small-cells have a range of approximately 100 metres.

Femtocells were proposed to extend the concept of picocells to home networks, in particular. They have limited output power, between 10 and 20 dBm, and capacity as they serve 4 to 6 users. These type of small-cells can be deployed in a variety of scenarios. A typical deployment is in a rural environment, where a femtocell enables access to mobile network for users which are typically under a coverage hole but with a reliable Digital Subscriber Line (DSL) connection. As it happens homes in rural areas usually lack the macro cell coverage, but some already have access to high data rate Internet, making it an ideal scenario to deploy femtocells. Another use case case for femtocells is an enterprise environment, where the low capacity of femtocells is typically enough to cover a number of offices. The major advantage of femtocells is the fact they are directly installed by the end users inside their homes and have a maximum range of approximately 30 metres. This will ensure good coverage for subscribers. For operators, femtocells are a cheap solution because they are paid by customers.

2.3. Propagation Models and Databases

The overall objective of mobile operators is to satisfy users needs with adequate coverage and QoS. The performance of wireless communication systems depends in a fundamental way on the mobile radio channel. Consequently, predicting the propagation characteristics between the transmitters and receivers is crucial for the design and installation of a radio network communications system. All computations and simulation procedures depend on reliable propagation models. A propagation model is a formulation that intends to characterise and predict radio wave propagation. The basis for any

propagation model is a database, which describes the propagation environment. Several propagation models have been developed and proposed for cellular systems operating in different environments (outdoor, urban, suburban, rural, and indoor) but there are generally three different types of propagation models: empirical models, deterministic models and semi-empirical models.
An empirical model is based on observations and measurements. These are useful to study the general behaviour or to enable a rough estimation of the number of required cells in a large area. The classification of empirical models can be further divided into time dispersive and non-time dispersive. Time dispersive provides information about time dispersive characteristics of the channel, like the multipath delay spread of the channel. Non-time dispersive models consider various parameters, such as distance, antenna heights, frequency and transmitter power to predict average path loss.
The Okumura Model and the Okumura-Hata Model were some of the first empirical models developed that served as groundwork to many others. The COST-231 Hata Model, based on the previous ones, is another commonly used empirical model.
The Standard Propagation Model (SPM), used in radio network planning software, is a propagation model based on formulas of Okumura and Hata that was adapted to perform signal coverage predictions in the frequency range of 150 MHz to 3500 MHz and for distances between 1 km to 20 km. The SPM is best applied on mobile technologies such as LTE and LTE-A.
Semi-empirical are based on a combination of measurements and theory and attempt to interpret field data based on theoretical principles. The first site-specific propagation models were semi-empirical and were based on detailed terrain characteristics extracted along the individual propagation paths between transmitter and receiver. These models use low resolution geographic data but still manage to obtain reasonably fair results for coverage predictions in urban areas. They are, however inefficient when it comes to indoor coverage estimates in dense urban areas. The COST 231 Walfisch-Ikegami is considered a semi-empirical model used to predict urban environments. This model is an extension of COST-231 Hata model and it can be used for frequencies above 2000 MHz.
Deterministic models are numerical methods that simulate radio waves propagation by reproducing the physical propagation phenomena. These models use a specific location for the transmitter and the receiver to provide a reliable and thorough estimation of the path losses and the channel characteristics. They rely on terrain descriptive features (altitude, the geometry of the buildings, materials used in construction) to simulate the shadowing effect that a signal experiences to provide a correlated spatial variation of the path loss.
Dominant Path Models (DPM) are another type of propagation models widely used in radio network planning. A DPM does not rely only on the direct ray (like empirical models) and it does not consider hundreds of rays for a single radio link (like ray tracing), as pictured in Figure 3.

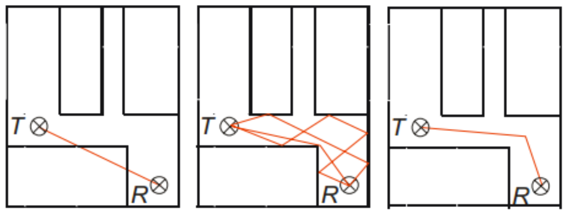

Figure 3: Empirical models (left), Ray Tracing (middle) and DPM (right) (extracted from [5]).

Instead it focuses on the most dominant path between transmitter and receiver. The Urban Dominant Path (UDP) model is one of the dominant path models that was developed for the prediction of the field strength specifically in urban environment. The algorithm of DPMs can be resumed in two different stages. First, the dominant paths have to be determined and then the prediction of the path loss for each path must be calculated. The dominant path must lead via convex corners from the transmitter to the receiver. For the determination of the path, a tree with all convex corners is computed starting with the corners visible from the transmitter.

As mentioned above, propagation models perform their predictions using information from terrain databases. The environment to be analysed and predicted is stored in a database file. But depending on the type of scenario (indoor, urban or rural), the resources available and the overall level of accuracy intended for each project a different description of the relevant obstacles is necessary.
The most rudimentary type of database used nowadays is a 2D database. It is composed by a height file or Digital Terrain Model (DTM) and a clutter file. The DTM consists in a digital model that represents the surface of the Earth, excluding vegetation as well as buildings and man-made structures. It contains the altitude values of the region and as such is characterised by a latitude Y, a longitude X and a specific resolution. The resolution is linked to the retrieval of the topographic data according to a given scale. The clutter file used in a 2D database describes the land use classification of the area in analysis including any features that impact the radio wave propagation. The clutter types or so-called clutter classes include natural environ-

ments: river, forest, ocean or man-made: industrial, suburban, dense urban, to name a few. The appropriate number of clutter classes depends on the geographic area. The combination of the DTM and the clutter types result in a 2D database because the altitude only refers to the height of the terrain and no clutter height information is usually provided. The propagation models that use 2D databases are empirical ones. In empirical models the path loss is calculated for the direct path between the transmitter and receiver and the topography of the terrain is only used to calculate obstructions. According to the given clutter category of the area, an attenuation or gain is added to the total path loss.

Another type of database used is a 2.5D database. While it also consists of a DTM and clutter categories it includes the average height of each scenario by introducing the clutter heights. Each specific category will have a preassigned average height, for example a low density urban area will have an average height of 20 metres and an area classified as a village might have an average height of 6 metres. If a higher accuracy is necessary, subcategories with a specific height assigned to it can be created within a clutter class. This method provides with a better correspondence with the real environment. For example, a scenario labelled as dense urban can be divided in two, one with an average height of 15 metres and the other with 20 metres.

The most comprehensive and detailed type of database is a 3D database. Like previous databases it uses a DTM and clutter types (it may or may not include the clutter heights) but incorporates the height and contour of the buildings (3D Building Vectors). When using a 3D database, each of the buildings will have its own height and shape represented as close to reality as possible, unlike previous databases.

3. Methodology

This sector presents the methodology used in this work.

3.1. Propagation Models Used

The existing LTE network, operating at 1800 MHz, was configured in the 9955 RNP tool. All the necessary information regarding each site, transmitter and cell was included to obtain accurate predictions.

The first propagation model tested is Okumura-Hata. This model established empirical mathematical relationships which described the graphical information of the Okumura model. The equation describing the average path loss in an urban area is given by:

$$PL = 69.55 + 26.16log_{10}(f) - 13.82log_{10}(h_T) + [44.9 - 6.55log_{10}(h_T)]log_{10}(d) - H(h_R, f) \quad (1)$$

where:
f: frequency in MHz;
H_T: transmitter height in metres;
d: distance in kilometres;
H(h_R,f): correction factor for the mobile antenna height.

The correction factor is computed differently according to the size of the area in question. In this case:

$$H(h_R, f) = \begin{cases} 8.29(log_{10}1.54h_R)^2 - 1.1, \\ f \leq 200MHz \\ 3.2(log_{10}11.75h_R)^2 - 4.97, \\ f \geq 400MHz \end{cases} \quad (2)$$

where:
f from 150 MHz to 1500 MHz;
h_T from 30 m to 200 m;
h_M from 1 m to 10 m;
d from 1 km to 20 km.

This model will only be applied with a 2D database as it is empirical.

The COST 231 Hata Model will also be used. This model extends the previous one to cover the frequency range of 1500 MHz to 2000 MHz. The other validity conditions are maintained.

The path loss is given by:

$$PL = 46.3 + 33.9log_{10}(f) - 13.82log_{10}(h_T) + [44.9 - 6.55log_{10}(h_T)]log_{10}(d) - H(h_R, f) + C_m \quad (3)$$

where:

$$H(h_R, f) = \begin{cases} 8.29(log_{10}1.54h_R)^2 - 1.1, \\ f \leq 300MHz \\ 3.2(log_{10}11.75h_R)^2 - 4.97, \\ f \geq 300MHz \end{cases} \quad (4)$$

$$C_m = \begin{cases} 0dB, \text{medium-sized city or suburban areas} \\ 3dB, \text{metropolitan areas} \end{cases} \quad (5)$$

Similarly, to the Okumura-Hata model, the predictions using the COST 231 Hata Model will only use a 2D database given its empirical nature.

The SPM will also be tested. The model is based on Equation 6 and each of the K parameters can be adjusted according to specific conditions such as terrain profile, diffraction mechanisms, morphology of clutter classes and the effective height of the transmitting and receiving antennas. [4]

$$P_R = P_T[K_1 + K_2 log_{10}(d) + K_3 log_{10}(hT) + K_4.DiffractionLoss + K_5 log_{10}(d).log_{10}(h_T) + K_6 h_R + K_7 log_{10}(h_R) + K_{CLUTTER}.f_{CLUTTER} + K_{HILL}] \quad (6)$$

where:

P_R: received power in dBm;

P_T: eirp in dBm;

h_T: effective height of the transmitter in metres;

h_R: effective height of the receiver antenna in metres;

d: distance between the receiver and the transmitter in metres;

Diffraction Loss: losses due to diffraction over an obstructed path in dB;

$f_{CLUTTER}$: weighted average losses due to the clutter.

The specific recommended adjustment coefficients will not be presented as they are classified by Nokia as internal use only. The SPM will be used with the 2D and 2.5D database and the formula will be adapted for each one according to Nokia's internal guidelines. For the coverage prediction using a 2D database, 9955 computes the total path loss using the topographical information of the terrain provided in the DTM files and the clutter class of the area. Each clutter class will have assigned a specific loss value that is then added to the total path loss equation. The loss values used correspond to Nokia internal guidelines.

To compute the predictions with the 2.5D database, 9955 will use the path loss formula and added losses according to the clutter class like in the previous case but it will also consider an average height for each clutter class, on top of the terrain topography. The specific height given to each clutter class was also defined after analysing Nokias internal guidelines.

The main difference between a 2.5D and a 3D database consists in the building vector file. The vector file describes each building height, shape and orientation in detail. Another propagation model tested was the WinProp UDP. This model is known to be a trade-off between computation complexity and accuracy. The 3D building database was preprocessed prior to the prediction computation, using Wallman a module that is part of the WinProp wireless network planning software package.

3.2. Data Adjustments

Some corrections had to be implemented to reduce any inconsistencies in the data obtained in the walk test and to make it comparable to the results of the predictions obtained with 9955.

A buffer area was used in the coverage by area analysis. This buffer area was created by analysing and connecting each position of the walk test to create a path. After the path was created, it was transformed in an area using QGIS.

By using the buffer most of the area analysed is categorized as Open Area which corresponds to the actual streets. Considering 9955 adds a specific loss value according to the clutter class, if this correction was not performed, the values of the predictions would be over-estimated because they would include the loss value associated to each building or other obstacles.

It is relevant to add that any errors found while analysing the walk test points were also corrected. This means any walk test location that was shown to be in an indoor situation was placed in the nearest possible outdoor position, since it is known the walk test only took place outdoors.

The data obtained in the walk test was also treated to eliminate any inconsistencies. If at a given point, with the same coordinates, different signal values were recorded by the same transmitter an average value was then used.

The measurements recorded during the walk test include the Reference Signal Received Power (RSRP) and Reference Signal Received Quality (RSRQ). The RSRP is the average of power levels received across all reference signal symbols within the considered measurement frequency bandwidth. The RSRQ is the ratio of RSRP and the E-UTRA Carrier Received Signal Strength Indicator (RSSI). The E-UTRA carrier RSSI comprises the total received wideband power observed by the UE. The signal values recorded during the walk test correspond to the signal level from the best server.

To sum up the propagation models simulated with the corresponding databases are listed in Table 1.

Table 1: Propagation Models and Databases Tested

Model	2D	2.5D	3D
Okumura - Hata	X		
COST 231 - Hata	X		
SPM	X	X	
WinProp UDP Outdoor			X
WinProp UDP Indoor			X

4. Results

This section presents the results of the different analysis performed in this work.

4.1. Coverage Results

In an initial stage a coverage analysis by area was performed to compare the Cumulative Distribution Functions (CDF) of the several models with the walk test resuls.

In Figure 4 the RSRP results of the walk test are presented. The scale goes from RSRP levels higher or equal to -55 dBm to RSRP levels higher or equal to -115 dBm, with a step of -5 dBm.

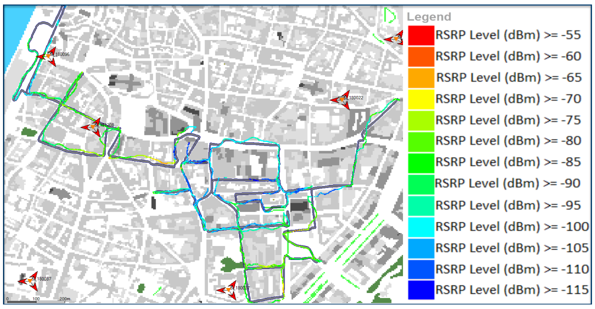

Figure 4: RSRP Results Obtained in the Walk Test

The numerical results of the RSRP levels obtained in the walk test are presented in Figure 5.

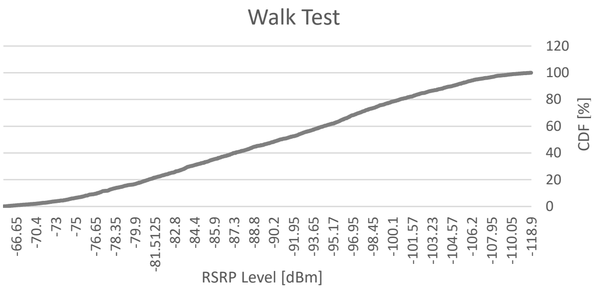

Figure 5: CDF of the Walk Test RSRP Results

The highest value of RSRP measured throughout the route was -60.8 dBm. This value was found only once among all the samples and it corresponds to 0.024 % of all the valid measurements. The graph shows that as the RSRP level decreases, more samples are included. According to this results, 50 % of the samples have a RSRP level greater than or equal to -90.8 dBm. The lowest value of RSRP level measured during the walk test was -118.9 dBm.

The results obtained from the predictions with the propagation models were all performed considering the same buffer area. In Figure 6 a graph depicting the RSRP coverage results of every propagation model is presented. The SPM 2.5D appears to be highly optimistic with a CDF curve distant from the curve of the walk test results. The SPM 2.5D simulated values as high as -58.8 dBm while the highest values obtained during the walk test were -60.8 dBm. In comparison the highest value calculated by SPM but with a 2D database was -63.8 dBm. The highest value obtained by the simulation of Okumura-Hata model was -67.7 dBm and with COST 231-Hata was -72.6 dBm. The simulations with WinProp UDP model show that it ob-

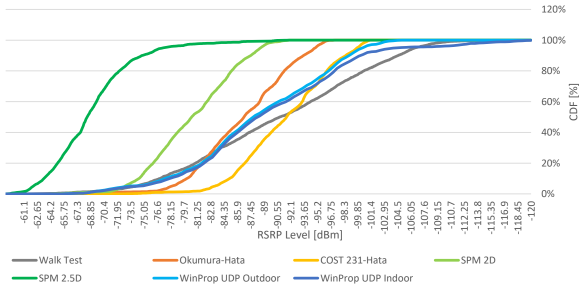

Figure 6: Comparison of RSRP Coverage Predictions

tained values more aligned with the measurements retrieved during the walk test. Both WinProp UDP models predicted -65.5 dBm as the highest RSRP level in the buffer area.

The results can also be interpreted by separating the results by power level. In the lower range of signal power the WinProp UDP Indoor is the model that reaches an RSRP Level closest to the one obtained in the walk test. In this case for a CDF value of 95 % UDP Indoor obtained -104.25 dBm while the walk test measurements resulted in -106.57 dBm.

As the signal power increases, the WinProp UDP Outdoor and the COST 231-Hata model also tend to approximate more to the walk test results. When the walk test obtained -98.85 dBm for a CDF value of 75 %, the result of the COST 231-Hata model was -95.7 dBm while UDP achieved -95.25 dBm and -96.3 dBm, for the outdoor and indoor mode respectively. When the signal power increases and crosses the -85 dBm mark, the Okumura-Hata starts to obtain much better results than the COST 231-Hata model. For a CDF value of 25 % the walk test obtained an RSRP level of -82.55 dBm while the Okumura-Hata also attained -82.55 dBm and the COST 231-Hata result was-87.55 dBm In the higher range of signal power both WinProp UDP models closely align with the walk test results, as well as the SPM 2D until around -72 dBm.

The same analysis was performed for the RSRQ measurements. The results of the RSRQ levels obtained in the walk test were also added to 9955 and are represented in Figure 7. The scale portrayed in the figure ranges from lower RSRQ values such as -22 dB to higher ones like -6 dB. Although the RSRQ levels measured in the walk test did not reach a value lower than -17.2 dB, the scale includes some lower values to account for the results obtained in the predictions of the different models.

The numerical results of the RSRQ levels obtained in the walk test are presented in Figure 8. As seen in the graph, the results are presented using the CDF in the vertical axis and the RSRQ level measured in

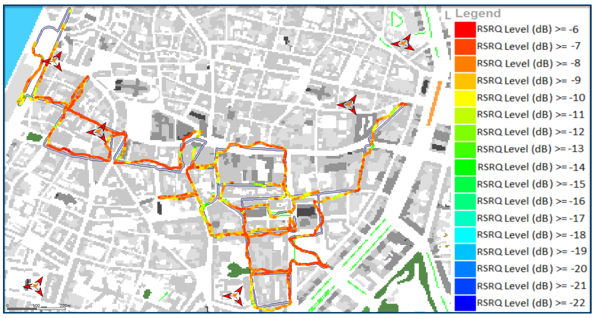

Figure 7: RSRQ Results Obtained in the Walk Test

dB in the horizontal axis. The graph shows that the

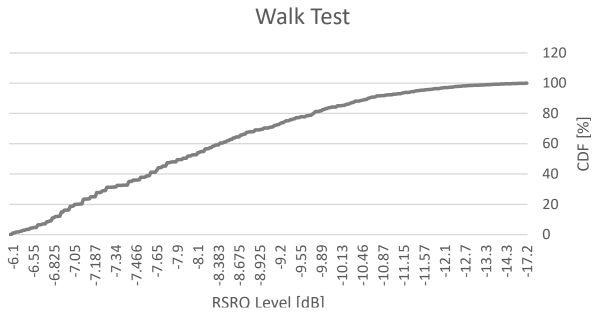

Figure 8: CDF of the Walk Test RSRQ Results

highest value of RSRQ measured throughout the route was -6 dB, which corresponds to 0.253 % of all the values obtained. By observing the graph one concludes that 50 % of the samples have a RSRQ level greater than or equal to -8.95 dB. The lowest value of RSRQ level measured during the walk test was -17.2 dB. Each of these measurements correspond to the signal received from the best server at that moment and exact location.

In order to compare the RSRQ results obtained by every model, a graph with the cumulative distribution function of the results is shown in Figure 9.

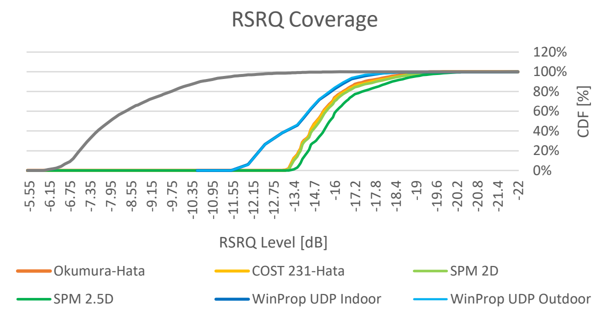

Figure 9: Comparison of RSRQ Coverage Predictions

As opposed to the RSRP results, none of the models used for the RSRQ coverage prediction immediately stands out as the best fit, seeing as the walk test clearly obtained results with a higher RSRQ level. The walk test measurements of the RSRQ range from -17.2 dB to -5.8 dB. The model that obtains a highest value of RSRQ is the WinProp UDP with -11.5 dB for both the indoor and the outdoor mode. With the other 4 models the highest value of RSRQ is around -13 dB.

4.2. Validation of Results

A statistical analysis of the accuracy of each model studied is necessary. The following statistical performance metrics were used: Mean Absolute Error (MAE) and Standard Deviation (SD). These metrics were calculated in linear units and converted back to dB.

$$MAE = \frac{1}{N}\sum_{i=1}^{N} |S_i^M - S_i^P| \tag{7}$$

$$SD = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (|S_i^M - S_i^P| - \mu)^2} \tag{8}$$

where μ is the absolute error.

The MAE and SD of the RSRP point-to-point results are presented in Table 2. According to the results in the table the propagation model that obtains the best approximation to the walk test is Okumura-Hata model with a MAE of 13.533 dB.

Table 2: Statistical Analysis of RSRP Results

Model	MAE (dB)	SD (dB)
Okumura - Hata	13.533	17.333
COST 231 - Hata	14.190	21.188
SPM 2D	17.953	21.507
SPM 2.5D	29.213	33.087
WinProp UDP Outdoor	15.621	24.086
WinProp UDP Indoor	26.466	38.950

In Table 3, the statistical analysis of the RSRP results is performed but with a variation. In this case, the samples that had an absolute error higher than or equal to 30 dB were excluded. This analysis attempts to reduce the effect of the outliers on the overall results. According to these results, the model that obtained the lowest MAE is now WinProp UDP Outdoor with 12.427 dB. WinProp UDP Indoor also obtained a much lower MAE than in the previous case.

The results were also divided according to power level in order to better analyse the general behaviour of each model. In Table 4 only walk test samples with a RSRP value lower than or equal to -85 dBm were considered. On the other hand, in

Table 3: Statistical Analysis of RSRP Results excluding samples with an AE higher than 30 dB

Model	MAE (dB)	SD (dB)
Okumura - Hata	13.486	17.149
COST 231 - Hata	12.659	17.958
SPM 2D	17.660	20.877
SPM 2.5D	22.833	23.866
WinProp UDP Outdoor	12.427	17.519
WinProp UDP Indoor	13.712	18.553

Table 4: Statistical Analysis of RSRP Results-Walk Test Samples ≤ - 85 dBm

Model	MAE (dB)	SD (dB)
Okumura - Hata	13.800	16.584
COST 231 - Hata	9.182	11.280
SPM 2D	19.522	22.195
SPM 2.5D	30.867	33.769
WinProp UDP Outdoor	11.955	15.338
WinProp UDP Indoor	11.031	16.534

Table 5: Statistical Analysis of RSRP Results - Walk Test Samples > - 85 dBm

Model	MAE (dB)	SD (dB)
Okumura - Hata	12.927	18.346
COST 231 - Hata	17.858	23.433
SPM 2D	8.384	11.104
SPM 2.5D	14.606	15.636
WinProp UDP Outdoor	18.942	26.439
WinProp UDP Indoor	31.270	41.399

Table 5 only the samples with a RSRP level higher than -85 dBm were used.

The propagation model that achieved an overall lower MAE in the lower power scenario was COST 231-Hata with a MAE of 9.182 dB. It is worth mentioning that WinProp UDP Indoor had a clear improvement of its error. In the low power scenario its MAE was 11.031 dB whereas in the general analysis its MAE was 26.466 dB. For the higher power signal scenario, the model that achieved the lowest MAE was SPM 2D with 8.384 dB.

An equivalent analysis of the point-to-point comparison of the RSRQ results was elaborated. The most relevant results of all the analysis are depicted in Table 6.

According to these results, the propagation model that obtains the lowest MAE is WinProp UDP Indoor with 6.319 dB. In this comparison however, the difference between the MAE of each model is much lower than in the RSRP case. The model that obtained the highest MAE was SPM 2.5D with 8.127 dB, which is a difference of only 1.808 dB.

Table 6: Statistical Analysis of RSRQ Results

Model	MAE (dB)	SD (dB)
Okumura Hata	7.343	4.733
COST 231 Hata	7.406	4.859
SPM 2D	7.573	5.052
SPM 2.5D	8.127	5.700
WinProp UDP Outdoor	6.319	3.634
WinProp UDP Indoor	6.326	3.594

5. Conclusions

Initially, the work proposed in this thesis aspired to compare the results of the same propagation model using different types of databases and different propagation models using the same type of geographical databases. However, the analysis of several propagation models was found to be more difficult than expected.

The validity of the walk test is another factor to be taken into consideration. There are several possible sources of errors. Apart from the mobile terminal error (which depending on the vendor might be up to 3 dB), positioning also suffers from inconsistencies, which added another error factor by requiring artificial correction of measurements that had their GPS locations registered indoor when it is known all walk tests were outdoor. Also, it is important to note that the database of the sites' location is prone to errors, since the exact location of the antennas is most of the time unknown and assumed to be the geographical location given for the site.

Moving into the analysis of the actual results, a first outlook showed Okumura-Hata and COST 231-Hata obtained the lowest values of MAE, which is somehow surprising considering that these propagation models are the most generic ones. Okumura-Hata obtained a MAE of 13.533 dB, while COST 231-Hata obtained 14.190 dB of MAE. Both models are deterministic and based on the Okumura model. As such, these models are ideal for urban cities with many low buildings. Antwerp, as it happens, falls particularly well into this scenario, especially in the city centre. The citys architecture is very regular with perpendicular streets and most buildings of similar height, particularly in the area where the walk test took place. The good performance of these models can partly be justified by these factors. In addition, these measurements were performed outdoor and at ground level which corresponds to the conditions these models are applied.

Still regarding RSRP, going into more detail, it was decided to avoid samples with an absolute error higher than 30 dB and those samples were excluded in a second analysis. This procedure intended to mitigate the effect of outliers, as the logarithmic measurement has a lot more impact in the overall statistical distribution of the results. Therefore, this analysis aims to provide a wider perspective of the results.

According to this analysis, the model that obtained the lowest value of MAE was the WinProp UDP Outdoor, with a value of 12.427 dB.

RSRP was also analysed according to the range level. The MAE and SD were calculated for two different RSRP intervals. In the first case samples of the walk test that had RSRP lower or equal to -85 dBm were analysed separately. This scenario attempts to interpret the results of the different models when the mobile terminal is located at a considerable distance from the base station. The model that obtained the lowest MAE in this case was COST 231-Hata. The second scenario only analyses walk test samples with a power level higher than -85 dBm. In this situation, when the receiver is located closer to the base station the model that obtained the lowest MAE of all the different simulations was SPM 2D, which also registered the lowest standard deviation.

The model that overall seems to show a best performance regardless the method of analysis is WinProp UDP Outdoor. This model presents almost the best MAE when all samples are analysed together and a good match when splitting the RSRP into different categories, although for higher RSRP levels the MAE is slighlty degraded. In the area analysis section, WinProp UDP Outdoor is also the model that more consistently approximates to the results measured in the walk test.

When looking to RSRQ, it shows less variation than the RSRP. A possible cause for this is the fact the RSRQ measures the quality of the received reference signal over the RSSI, which is a measure of the entire bandwidth highly associated with other cells interference. In this case both numerator and denominator are equally affected by the error. In the first analysis of the RSRQ results, the model that obtained the lowest error was WinProp UDP Outdoor with a MAE of 6.319 dB.

Another important aspect is the fact that, incidentally, all base stations were located above rooftop level within the scenario under analysis. This is a typical scenario when a macro network requires capacity expansion and the proposed solution is to deploy small-cells. Under these conditions the traditional approach is to plan small-cells for coverage holes that the existing macro sites cannot cover or to improve network quality in locations where the existing macro network does not provide enough radio quality to allow higher order modulation schemes. However, it has not been possible to assess the behaviour of these propagation models applied to outdoor small-cells, traditionally deployed at street level at heights no higher than 2 floors and where most of the radio propagation happens below rooftop level.

Regarding future work, it would be interesting to validate some of these results by recreating this study in other urban areas or even expand it to different scenarios and assess its validity. An equally valid experiment would be to recreate this exact study but changing the terminal and increasing the route so as to cover more clutter classes, across a wider area to better complement the measurement scenario and increase the amount of measured samples.

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