Performance Evaluation of UMTS/HSPA+ Data Transmission for Indoor Coverage

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Abstract—The main objective of this work was to study and quantify the data rate transmission performance for a UMTS/HSPA+ system in indoor scenarios, giving special emphasis to capacity and coverage aspects. These goals were accomplished through the development and implementation of two models: the Single- and Multi-User models. A measurement campaign was conducted to obtain a model for signal attenuation, which was input in both models. In order to verify the indoor data rate performance, simulations were made by changing different parameters. In DL, the most influencing factor is the presence of interference, lowering the average indoor throughput in isolated buildings. In UL, the available signal power is the key factor, in which higher buildings have greater average throughputs due to the availability of signal in the upper floors. The number of penetrated walls also decreases the data rate, as well as the desired coverage percentage. The floor height gain verified in terms of signal is also present in the data rate, with an average data rate increase of 3.25% in DL and 8.99% in UL. Generically, the data rate reductions are greater in UL due to the lower transmitting power and the shorter throughput range.

Keywords—UMTS/HSPA+; Capacity; Coverage; Indoor; Data Rate Performance; Measurements.

I. INTRODUCTION

Mobile phones are nowadays used everywhere, outdoors and indoors. Not only are the mobile phones used for data traffic, but more and more modem sticks are spreading among the users in order to get mobile data connections at high data rates. Since the users spend a majority of their time inside buildings, it is important for the mobile communication operators to cover indoor areas. In these environments, customers demand a good coverage and quality of service. Nevertheless, these systems were not deployed to satisfy specifically these requirements.

Especially in Universal Mobile Telecommunications System (UMTS) networks with macro cells it is very difficult to reach sufficient indoor coverage due to the higher carrier frequency and the higher required throughput compared to Global System for Mobile Communications (GSM). By installing extra cells and tolerating high transmitting power per link, it may be possible to reach the required coverage. However, network operators also try to avoid over dimensioning of their networks as this results in high costs for the additional cell sites or in a waste of radio resources. Thus, in order to reach a satisfying indoor coverage without great expenses, it is necessary to have a prediction of the effective coverage. Particularly within buildings in urban areas the prediction of the received power levels is a very complex task due to the high attenuation imposed by the building materials.

While the number of UMTS subscribers and the traffic of UMTS networks increase, indoor users generate more and more traffic. Studies show that more than 70% of the wireless broadband usage is generated by indoor users [1]. For such a high indoor wireless broadband usage, the indoor environment becomes a critical area for UMTS network coverage. Particularly, the indoor High Speed Downlink Packet Access (HSDPA) performance is of most interest for mobile operators and system vendors due to concern about the impact of building penetration loss that plagued the first and second generation cellular systems [2].

The surrounding environment is a key factor in mobile communications. Wave propagation models are extremely important to guarantee a good coverage and capacity planning, since one can use them to determine propagation characteristics. Relevant to this work are the small macro-cells outdoor models since they are used for dimensioning in urban scenarios. The path loss expression can be achieved by the combination of outdoor and indoor losses, as shown in Fig. 1:

\[ L_p[\text{dB}] = L_{p\text{ outd}}[\text{dB}] + L_{p\text{ ind}}[\text{dB}] \]  

where:
- \( L_{p\text{ outd}} \) is the path loss attenuation given by the outdoor model;
- \( L_{p\text{ ind}} \) is the path loss attenuation given by the indoor model.

Figure 1. Illustration of the outdoor and indoor losses (extracted from [Corr09]).
One outdoor model is suggested by [3], COST231 - Walfisch-Ikegami (WI), an empirical model developed for urban environments, considering distances lower than 5 km. When the mobile equipment (MT) is not between buildings and the base station (BS) is on the building top adjacent to the mobile terminal (MT), the path loss can be calculated according to the Walfisch-Bertoni model [3]. In this case the reflected ray in the building no longer exists therefore one cannot use the WI model. This particular situation is used when the MT is indoors and there is only one ray connecting the MT and the BS. An extra attenuation factor should be taken into account when the signal is diffracted from the rooftop to the MT. This factor is added to the free space loss factor of the path loss expression.

Concerning the indoor models, COST231 [4] suggests several investigated models, such as the Multi-Wall model (MWM), which takes into account the free space loss plus losses like the walls and floors penetration loss by the direct path between the transmitter and the receiver.

In the early days, interference was not a great problem in mobile communication systems. With the growth of these systems and the number of users, interference is nowadays a great issue for the operator. Smaller size cells and less transmitting power are needed in order to reduce the number of users per cell, allowing more bandwidth and less power per user. A few models can be found about this subject. The interference model shown in [5] is based on simulations. Several parameters were analysed during the simulation procedure, namely the distance between the BS and the MT, the MT building height, the street width and the BS antenna tilt. For the purpose of this work only the MT building height and the distance are included, since the rest of the parameters are not so relevant to the desired analyses.

As state of the art, in [6], [7] and [4], statistical studies on the indoor signal attenuation in urban scenarios are presented, comprehending both GSM and UMTS bands and not taking into consideration the building type. In [8] and [9], measurements on both GSM and UMTS bands are performed, taking the building type into account in the attenuation results (also statistical). Few studies can be found on indoor data rate performance. Tang and Fitzpatrick [2] study the impact of building penetration on HSDPA throughput. Indoor and outdoor HSDPA performance measurements were carried out in a live HSDPA network for a mobile located near the cell edge in a suburban environment. The measurements results show that the greatest difference between the indoor and outdoor data rates occur during the low load period (when the system is noise-limited and therefore the building penetration loss has the greatest impact). During the high traffic periods, the difference between indoor and outdoor performance is minimal due to full power transmission from all base stations resulting in an interference-limited environment. In the analysed periods the outdoor data rate is higher than to the indoor data rate by 20 % to 40 % for the low load period and about 10% for the high load period.

The purpose of this work is to study and quantify the impact of the indoor environment on the available UMTS/HSPA+ throughput for different types of urban scenarios, giving special emphasis to capacity and coverage aspects. These goals were accomplished through the development and implementation of two models: the Single-User and the Multi-User one. A measurement campaign was conducted to obtain a model for indoor signal attenuation, which was input in both Single- and Multi-User models.

This work was made in collaboration with the Portuguese mobile telecommunications operator Vodafone Portugal, several technical details and work assumptions being discussed during the project.

In Section II, the Single- and Multi-User models are presented, giving an overview of out- and indoor propagations models, as well as the model for interference calculation. Section III contains a brief description of the simulator. Section IV includes a description of the analysed scenarios, the results obtained in the measurements and the simulation results. Finally, conclusions are shown in Section IV.

II. MODEL DEVELOPMENT

Two different models were implemented: the Single- and the Multi-User one. The former concerns the modelling of the available resources for a Single-User in the network, whereas the latter gives information about the total capacity in a multiple user network, given a desired data rate for each user.

The Single-User model is intended to provide an understanding of the requirements needed to serve a user located indoors, considering different building and room types. It is possible to calculate the available throughput given for a Single-User, varying several parameters of both outdoor and indoor environments.

The aim of the Multi-User model is to quantify the reduction in the number of users for a given throughput in a defined urban scenario, assuming users are uniformly distributed along the radius of the cell. Although the outdoor scenario is left unchanged, the model randomises the indoor scenario according to the available building and room types, building coverage and MT height. This model takes the both network and propagation restrictions into account: the number of available HSPA+ Downlink (DL) codes, the available signal power and the existing interference power in the surroundings of the MT.

A. Outdoor Model

Concerning the outdoor environment, [5] proposes six different path loss scenarios:

- When the MT is served by one BS on the building top, Fig. 2, case 1. The calculation is done according to (6). In this particular case, the outdoor reference position is on the building rooftop and not on the middle of the street;
- When the distance between BS and MT is less than 20 m and there is Line-of-Sight (LoS), Fig. 2, case 2, free space attenuation (4) plus indoor loss (6) are the propagation models used to obtain the total loss;
- When the BS is located on the top of an adjacent building, the distance between BS and MT is less than 20 m and BS is in Non-Line-of-Sight (NLoS) with MT, the path loss is calculated by free space plus extra attenuation (5) added to (6), Fig. 2, case 3;
- When the BS is in the adjacent building façade and there is LoS with all the floors, the path loss is calculated according to (4) if the distance is less than 20 m, and (2) if it is more than 20m, plus (6), Fig. 2, case 4;
• When the BS is in LoS and more than 20 m far away to the MT, COST 231 - Walfisch-Ikegami (2) plus (6) are the models applied, Fig. 2, case 5;

• For last situation, Fig. 2, case 6, when the BS is in NLoS and more than 20 m far away to the MT, the calculation is done according to (3) plus (6).

\[
L_p [\text{dB}] = 42.6 + 26 \log(d[km]) + 20 \log(f[\text{MHz}]),
\]

(2)

\[
L_p [\text{dB}] = \begin{cases} 
L_0[\text{dB}] + L_{rs} [\text{dB}] + L_{mos} [\text{dB}] & \text{for } L_{rs} + L_{mos} > 0 \\
L_0[\text{dB}] & \text{for } L_{rs} + L_{mos} \leq 0
\end{cases},
\]

(3)

\[
L_0[\text{dB}] = 32.4 + 20 \log(d[km]) + 20 \log(f[\text{MHz}]),
\]

(4)

\[
L_{rs}[\text{dB}] = -20 \log \left[ \frac{1}{\sqrt{\pi \cdot k \cdot d_r[m]}} \left( \frac{1}{\Psi_{[\text{rad}]} - \frac{1}{2\pi - \Psi_{[\text{rad}]}}} \right) \right],
\]

(5)

where:

• \(d\) is the distance to the BS;

• \(f\) is the operating frequency;

• \(\Psi\) is angle between MT and roof-top corner;

• \(k\) is the propagation constant;

• \(L_{rt}\) and \(L_{msd}\) are the COST231-Walfisch-Ikegami model parameters, which mainly describe the loss between last roof-top and MT and the loss between BS antennas and the last roof-top, respectively [4].

• \(d_r\) is the distance between roof top and MT.

• Low-Integrated (LInt): a building up to 6 floors, being surrounded by other buildings with similar height (possibly contiguous);

• Low-Isolated (LIso): a building up to 6 floors, not being surrounded by other buildings.

For each floor of a given building, three categories of rooms were considered, as defined in [8]:

• Indoor Window (IW): a room with a window facing the outdoors;

• Indoor Daylight (ID): a room with one wall separation to the outdoors;

• Deep Indoor (DI): a room with two walls separation to the outdoors.

The calculation of the indoor loss is done according to (6), being based on the presented MWM. The indoor loss is referred to the outdoor signal power (in the middle of the street, as modelled by the outdoor model) for each room type, as shown in Fig. 3. It is modelled as a function of the coverage percentage, \(p\), \(u(p)\) being the inverse function of the indoor loss distribution. In order to model the received signal power by (6), one has to assume a log-normal distribution for the RSCP.

\[
L_{p_{\text{ind}}}[\text{dB}]_{\text{Floor } i}^{\text{IW,ID,DI}} (p) = \mu_{\text{Floor } i}^{\text{IW,ID,DI}} + u(p) \times \sigma_{\text{Floor } i}^{\text{IW,ID,DI}},
\]

(6)

where:

• \(\mu_{\text{Floor } i}^{\text{IW,ID,DI}}\) is the mean attenuation concerning floor \(i\) in room type IW, ID or DI;

• \(p\) is the desired building coverage (in percentage);

• \(u(p)\) is the function that describes the inverse indoor loss distribution;

• \(\sigma_{\text{Floor } i}^{\text{IW,ID,DI}}\) is the standard deviation concerning floor \(i\) in room type IW, ID or DI.

A linear model was created for the mean value of each room type, with a floor dependency in each trend, (7). The choice for a linear trend curve is due to the desire to define a trend of the attenuation along the building floors, allowing extrapolations to be performed.

\[
\mu_{\text{Floor } i}^{\text{IW,ID,DI}} = \mu_{\text{var}}^{\text{Floor } i} \times F_n + \mu_{\text{level}}^{\text{Floor } i},
\]

(7)

where:

• \(\mu_{\text{var}}^{\text{Floor } i}\) is the variable part of the mean attenuation, dependent of the floor number;

• \(F_n\) is the floor number;

• \(\mu_{\text{level}}^{\text{Floor } i}\) is the static part of the mean attenuation, independent of the floor number.

In order to obtain the indoor signal power, the outdoor reference power is affected by the indoor loss:
\[ P_{Rx \text{ind}} [\text{dBm}] = P_{Rx \text{outd}} [\text{dBm}] - L_{p \text{ind}} [\text{dB}], \] (8)

where \( P_{Rx \text{ind}} \) and \( P_{Rx \text{outd}} \) are the indoor and outdoor received signal powers, respectively.

C. Interference Model

The indoor interference model, expressed in (9), was based on the simulated reference values in [5]. Several minor changes were made in order to meet the requirements: the model must be variable with the distance to the BS and the MT building height, more specifically the number of floors in LoS/NLoS. Three different expressions are presented, two for DL and one for UL. The DL expressions are distinguishable by the building type, in which the LoS component does not exist in the Integrated one. The UL expression does not take into account the distance variation due to its distance independence shown in the simulations [5].

\[
\begin{align*}
I_{DL \text{ [dBm]}}^{\text{Integrated}} & = 1.23 \times N_{Floors}^{\text{LoS}} + 3.27 \times N_{Floors}^{\text{NLoS}} + 286.7 \times d_{[km]}^2 + 83.63 \\
I_{DL \text{ [dBm]}}^{\text{Isolated}} & = 1.23 \times N_{Floors}^{\text{LoS}} + 286.7 \times d_{[km]}^2 + 83.63 \\
I_{UL \text{ [dBm]}} & = -0.01 \times N_{Floors}^{\text{LoS}} - 111.15
\end{align*}
\] (9)

where \( N_{Floors}^{\text{LoS}} \) and \( N_{Floors}^{\text{NLoS}} \) is the number of floors in NLoS and LoS, respectively.

D. Capacity Model

The indoor and outdoor capacity model is derived from the Release 99 capacity and coverage models presented in [3]. The model considers that users are spread over the cell at the same distance from the serving BS. Thus, in UMTS, the BS power is split equally among active users, and the distribution of the orthogonality factor with distance presented in [15] is assumed.

Although it only accounts for the available received signal power and the nearby interference power through Signal-to-Interference-plus-Noise Ratio (SINR) computation, the capacity also depends on the number of available codes given by the BS. The main inclusion is the adjustment of the capacity expression to the number of codes available in HSPA+ DL. Although the number of served users can be higher, the 15 available codes for data transmission only allow the same number of users in the respective BS. For UL, the same approach is chosen, since UL requests are made from the same users that require DL capabilities. Other small adjustments had to be included, such as the exclusion of negative number of users. Equation (10) shows the model expression.

\[
N_{au} = \begin{cases} 
15, & N_{au} > 0 \\
\frac{10^{\frac{10 + \alpha_{l}}{10}} - L_{r[\text{dB}]}}{F_a \frac{\rho}{G_\rho} [1 - \alpha_{CO}] + \rho_l}, & N_{au} \leq 0
\end{cases}
\] (10)

where:
- \( r \) is the cell radius;
- \( \alpha_{ld} \) is the average power decay;
- \( F_a \) is the activity factor (which can be 50 % for voice and 100 % for data);
- \( i \) is the ratio of inter- to intra-cell interferences (which can be [40, 60] % in UL and 0 in DL);
- \( \rho \) is the Signal-to-Noise Ratio;
- \( \alpha_{CO} \) is the code orthogonality factor (typically [50, 90] %);
- \( LB \) is the link budget expression, defined in (11).

\[
LB \text{ [dB]} = P_{f_1} \text{ [dBm]} + G_f \text{ [dB]} - \rho \text{ [dB]} + G_p \text{ [dB]}
\]

\[ - N_{au} + G_{Rx} \text{ [dB]} - L_{rf} \text{ [dB]}, \] (11)

where:
- \( P_{f_1} \) is the power fed to the transmitting antenna;
- \( G_f \) is the transmitting antenna gain;
- \( G_{Rx} \) is the receiving antenna gain;
- \( L_{rf} \) is the sum of propagation losses and margins (such as fast and slow fading);
- \( \rho \) is the Signal-to-Noise Ratio;
- \( N \) is the total noise power;
- \( G_p \) is the processing gain.

In order to implement the described models, the UMTSIndCov simulator was developed in C++. The simulator can be split into four main blocks: configuration, measurements, simulation and results. The simulation type adopted for the simulator was the statistical approach (snapshot).

In the first block, several parameters can be changed in the outdoor model: BS and MT characteristics (transmission power, antenna gains and height), operating frequency and distance between the BS and MT. Concerning the indoor model, the user can decide the simulated building and room types, as well as the desired coverage and the building’s number of floors. The simulator also allows computing both propagations links (DL or UL) and different antenna configuration schemes, namely Single Input Single Output (SISO), Single Input Multiple Output (SIMO) and Multiple Input Multiple Output (MIMO).

In the measurements block, the set of parameters used in the indoor path loss model are identified, such as the signal attenuation between floors and walls. Additionally, and due to the lack of theoretical knowledge on the modulation usage, the percentage of each of the possible modulation schemes used in the measurements is identified. These parameters are extracted from the measurements and are included in the simulation block, more specifically in the indoor loss calculation, given by (6) and (7).

The simulation block is split in two parts, one for the Single and the other for the Multi-User model. Concerning the Single-User model, the outdoor path loss scenario is determined depending on the MT position in relation to the BS and LoS/NLoS conditions. Outdoor and indoor path losses are calculated according to the criteria in Fig. 1. The indoor interference power is also computed, according to (9). The total path loss value is deduced from the transmission power, using (8). The performance analysis is done depending on the link,
using (12) for UL and (13) for DL. After this, the modulation is chosen using the measurements results. The last step is to perform the SINR to throughput mapping, according to the available SINR-to-throughput models presented in [10], [11] and [12].

\[
\begin{align*}
\rho_{IN} [\text{dB}] &= P_{RI} [\text{dBm}] - (I + N) [\text{dBm}] + G_P [\text{dB}] \quad (12) \\
E_b / (N_0 + I_0) [\text{dB}] &= P_{Rx,\text{ref}} [\text{dBm}] - (N + I) [\text{dBm}] + G_P [\text{dB}] \quad (13)
\end{align*}
\]

where:
- \(P_{RI}\) is power at the input of the receiver;
- \(P_{Rx,\text{ref}}\) is the receiver sensitivity;
- \(I\) is the total interference power.

Regarding the Multi-User model, the outdoor scenario is simulated in the same terms as the Single-User one. The indoor scenario is generated randomly, considering uniform distributions for the following parameters: number of floors (up to 12, depending on the building type), building coverage percentage (from 0 to 100 %), building and room type. The total path loss value is deducted from the transmission power, (8). Before applying the capacity model, the desired data rate is mapped into SINR according to the models presented in [10], [11] and [12] and the modulation is set according to the measurements results. The capacity model is computed using (10), considering outdoor and indoor losses, distance between the BS and MT and SINR required for the desired data rate per user.

In the results block, the simulation output is saved in files: indoor physical (and application) throughput and the bit error probability for the Single-User model; the indoor and outdoor number of served users for the Multi-User model.

Several parameters are extracted from the analyses require knowledge on some statistical indicators, such as the average and standard deviation. The main output is the DL/UL throughput reduction. The reduction values are referred to the average throughputs: the indoor and maximum served users in the cell (the maximum number being 15 for HSPA+ DL).

\[
\begin{align*}
\Delta R^\text{Floor}_b [\text{Mbps}] &= R^\text{Outdoor}_b [\text{Mbps}] - R^\text{Floor}_b [\text{Mbps}] \times 100, \quad (14) \\
\Delta R^\text{Room}_b [\text{Mbps}] &= R^\text{Outdoor}_b [\text{Mbps}] - R^\text{Room}_b [\text{Mbps}] \times 100, \quad (15)
\end{align*}
\]

where:
- \(R^\text{Outdoor}_b\) is the average outdoor throughput;
- \(R^\text{Floor}_b\) is the average indoor throughput in floor \(i\);
- \(R^\text{Room}_b\) is the average indoor throughput in room \(x\) (which can be IW, ID or DI);
- \(\Delta R^\text{Floor}_b\) is the average throughput reduction between the outdoor and indoor values (in floor \(i\));
- \(\Delta R^\text{Room}_b\) is the average throughput reduction between the outdoor and indoor values (in which \(x\) can be IW, ID or DI room types).

The comparison between simulated and measured results is performed by means of a correlation factor between the two functions. The correlation coefficient between two random variables \(X\) and \(Y\) with their respective expected values and standard deviations is given by [16]:

\[
corr(X,Y) = \frac{\sum_{i=1}^{n} (x_i - \mu_X)(y_i - \mu_Y)}{\sqrt{\sum_{i=1}^{n} (x_i - \mu_X)^2 \sum_{i=1}^{n} (y_i - \mu_Y)^2}}
\]

The average difference of throughput reduction between consecutive floors, defined as the extra reduction going one floor up, is given by:

\[
\Delta R^\text{Floor}_b [\%] = R^\text{Floor}_b (i) - R^\text{Floor}_b (i-1)
\]

The throughput reduction can be defined as depending on signal attenuation, is given by

\[
\Delta N_{au} [\%] = \psi [\% \cdot \text{dB}] \times \Delta RSCP [\text{dB}] + \zeta [\%]
\]

where:
- \(\psi\) is the variable part, depending on signal attenuation;
- \(\zeta\) is the static part, independent of signal attenuation.

For the Multi-User analysis, an indicator was computed to measure the user reduction from outdoor to indoor scenarios:

\[
\Delta N_{au} [\%] = \frac{N_{au,\text{outdoor}} - N_{au,\text{indoor}}}{N_{au,\text{max}}} \times 100,
\]

where \(N_{au,\text{outdoor}}\), \(N_{au,\text{indoor}}\) and \(N_{au,\text{max}}\) is the number of outdoor, indoor and maximum served users in the cell (the maximum number being 15 for HSPA+ DL).

III. RESULTS ANALYSIS

Two types of analysis are performed in this chapter. In the first part, measurement campaign results are overviewed. In the second part, measurement results are compared to the simulation results for a reference urban scenario. Later, several simulations are performed and its results analysed, using a reference urban scenario and then changing some parameters. Both the Single- and Multi-User models are used in the simulation: the Single-User scenario considers there is only one user in the cell therefore all available resources are dedicated to this user, whereas in the Multi-User scenario, one considers that the users are uniformly distributed along a certain radius, performing services with different associated throughputs.

A. Scenarios Description

The scenario for all evaluations is a pedestrian environment, considering an almost static user at the street conditions.
level (3 km/h as defined in ITU Pedestrian A channel). This environment is situated in urban cells, with the associated fading margins. This scenario accounts for Isolated and Integrated buildings, with their height assuming values in the recommendations of COST231-WI. In order to fit better with the city of Lisbon’s characteristics (where the measurements were made), the lack of very high buildings forced the reduction of the building height range to [4, 36] m. Although the outdoor scenario is defined, it only serves the purpose of establishing a reference outdoor throughput value. The MT is set inside the studied building, both in Single- and Multi-User analyses. The indoor scenarios comprehend all the available previously defined room types.

The measurement campaign was performed in the city of Lisbon. The selected spots were the buildings inside the Technical University of Lisbon campus and three other buildings in dense urban areas of the city. These scenarios are highly representative of the different urban scenarios and fit the previously defined building types.

For the purpose of different analyses, a reference simulation scenario is created, considering a MT average distance to the BS in a dense urban area. All simulated scenarios are presented in Table 1. The antenna height is set to be 2 m above a 5-floor building, representing the average height of the buildings analysed in the reference scenario (with the exception of case 4 where the antenna is on the building façade). All presented values belong to the recommended values of COST231-WI in a typical urban situation.

**TABLE I. OUTDOOR MODEL PARAMETERS FOR THE SIMULATIONS IN EACH CASE SCENARIO.**

<table>
<thead>
<tr>
<th>Path Loss Case</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6 (Reference)</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage [%]</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50, 90, 95</td>
<td>50</td>
</tr>
<tr>
<td>Outdoor Distance [m]</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>30</td>
<td>120</td>
<td>250</td>
</tr>
<tr>
<td>Building separation [m]</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>60</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Street width [m]</td>
<td>34</td>
<td>30</td>
<td>30</td>
<td>50</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>Number of obstacles</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Antenna height [m]</td>
<td>17</td>
<td>17</td>
<td>10</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>BS building height [m]</td>
<td>15</td>
<td>15</td>
<td>13</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

The urban scenarios presented in Fig. 2 were proposed for an extensive throughput reduction analysis. Case 1 was excluded from the simulation set since it does not comply with the reality: signal does not go through the building floors but is reflected in the surrounding buildings and penetrates the building walls, degenerating in cases 2, 3 or 4. Therefore, the case 1 signal attenuation model was not available, since the required measurement procedure was not performed. For the remaining case scenarios, simulations on cases 2, 3 and 4 were performed with 95 % building coverage, due to the short distance to the BS. Otherwise, the analyses would be inconclusive, since, at such short distance (less than 20 m), SINR is high enough to obtain a saturated throughput, which does not evidence the throughput variation along the floors/rooms. Concerning cases 5 and 6, a different approach is taken, in which different distances between the BS and MT are tested in order to understand the throughput variation along the cell.

The general characteristics of the simulated scenario are described in Table 2, which were used in both measurement comparison and urban scenarios simulations. Most of the reference values were extracted from [3] and [13]. The BS radiation pattern was chosen from [14], the same as selected in [5].

**TABLE II. REFERENCE PARAMETERS FOR ALL SIMULATION SCENARIOS.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Fading Margin [dB]</td>
<td>4</td>
</tr>
<tr>
<td>Slow Fading Margin [dB]</td>
<td>7.6</td>
</tr>
<tr>
<td>BS Transmission Power [dBm]</td>
<td>42.48</td>
</tr>
<tr>
<td>Radiation Pattern</td>
<td>P7755.00</td>
</tr>
<tr>
<td>Mobile Equipment Transmission Power [dBm]</td>
<td>23.29</td>
</tr>
<tr>
<td>User Body Losses [dB]</td>
<td>9</td>
</tr>
<tr>
<td>Cable Losses [dB]</td>
<td>5</td>
</tr>
<tr>
<td>Frequency [MHz]</td>
<td>5</td>
</tr>
<tr>
<td>Noise Figure [dB]</td>
<td>0</td>
</tr>
<tr>
<td>UL</td>
<td>100</td>
</tr>
<tr>
<td>Standard Deviation [dB]</td>
<td>1</td>
</tr>
<tr>
<td>UL Margin [dB]</td>
<td>5</td>
</tr>
<tr>
<td>UL DBS Gain [dB]</td>
<td>1</td>
</tr>
<tr>
<td>UL BS Tilt [deg]</td>
<td>2</td>
</tr>
<tr>
<td>UL Frequency [MHz]</td>
<td>1</td>
</tr>
<tr>
<td>DL DBS Gain [dB]</td>
<td>2</td>
</tr>
<tr>
<td>UL BS Tilt [deg]</td>
<td>2</td>
</tr>
<tr>
<td>UL Frequency [MHz]</td>
<td>1</td>
</tr>
<tr>
<td>UL BS Tilt [deg]</td>
<td>2</td>
</tr>
<tr>
<td>UL Frequency [MHz]</td>
<td>1</td>
</tr>
<tr>
<td>UL BS Tilt [deg]</td>
<td>2</td>
</tr>
<tr>
<td>UL Frequency [MHz]</td>
<td>1</td>
</tr>
<tr>
<td>UL BS Tilt [deg]</td>
<td>2</td>
</tr>
</tbody>
</table>

**B. Measurements**

The measurement campaign allowed a hands-on approach in terms of quantifying the signal attenuation for different building and room types, following the classification proposed in [8]. The results from the campaign were inserted in the indoor model for each building and room type, allowing a complete characterisation of the signal inside the building.

Several buildings were measured, according to the proposed classification: buildings with more than 6 floors are considered High, otherwise considered Low; buildings surrounded by other buildings (contiguous or not) are considered Integrated, otherwise they are Isolated. The measured buildings fit perfectly in this classification: three High Integrated buildings, two High Isolated buildings, two Low Integrated buildings and two Low Isolated buildings. The measurement procedure was similar in all buildings, measuring the outdoor adjacent and opposite street side pavements and then the available room types in each floor, according to the number of separation walls to the outdoor: zero (Indoor Window), one (Indoor Daylight) and two (Deep Indoor). The received signal power and DL/UL throughputs were measured in almost every room, excluding the cases where no permission was granted. After data processing, a signal attenuation model was created, taking outdoor measurements as reference, and input in the model implementation, as shown in Table 3. Additionally, the measurements’ software provided information about the modulation usage in all measured sites, allowing the creation of another useful model to input in the simulator.

Not all measurements results were consistent, therefore, some results had to be extracted from [9], after assuring the model coherence with the measured data. The specific propagations conditions and the lack of throughput stability did not allow to take good conclusions, although some trend could be identified. Generically, the floor height gain is verified for all building types, i.e., the upper floors have a greater available signal power than the lower ones. Among them, the High buildings show lower attenuation due to the increase of signal availability in the upper floors (especially the Isolated case), increasing the mean signal power: High Integrated show an...
average attenuation of 12.02 dB (across all floors) and for High Isolated the average is 2.17 dB, whereas Low buildings show an average attenuation of 16.96 dB and 36.13 dB for Integrated and Isolated, respectively.

In throughput analysis, the floor height gain is not true for all buildings though. More specifically, High Isolated ones have too much exposure to signal power, increasing not only the desired one but also the interfering. SINR is therefore lowered, and throughput shows the opposite behaviour of signal power, usually being lower in the upper floors. This is particularly noticeable between the average throughput reduction (in percentage) of High Isolated and High Integrated buildings: the former suffers a -18.29 % reduction (therefore a gain relatively to the outdoor measurement), whereas the latter suffers a 22.79 % reduction, due to the stated reasons. Low buildings suffer a 13.15 % and 22.47 % reduction for High Isolated and High Integrated, respectively, due to the same reasons explained for the signal attenuation. The interference is typically noticeable in DL, whereas in UL it is not so evident. UL average reduction is -17.14 % for High Integrated and -76.90 % for High Isolated, which evidences the conclusions taken earlier: the signal availability is greater in the Isolated buildings, and so is UL throughput since the interference power is not so influencing as in DL. Regarding Low buildings, Integrated shows a -59.88 % reduction and Isolated a 20.34 % reduction. Although the result for HIso is reasonable, the same cannot be stated for the HInt buildings. This case underlines the low fidelity of the UL throughput collected data, since the UL maximum throughput is highly dependent on the transmission time interval (TTI) given by the BS scheduler, invalidating the supposed normal distribution of the measured data.

C. Simulations

In order to verify the indoor data rate performance, simulations were made by changing some parameters, such as the outdoor configuration between BS and MT, the indoor desired coverage and both room and building types.

1) Comparison with Model Results

The measurement results were compared to the reference scenario, showing similar trends in the majority of the cases: throughput suffers a greater reduction the inner the room is. In High Integrated buildings, not all room types were measured therefore no trend is available. Despite this, the simulated results show an average reduction (between room types) of 15.20 % and 16.51 % for DL and UL, respectively. In the measured case, the type of measured rooms only allows a DL analysis, its average reduction being 44.53 %. As for High Isolated buildings, simulated and measured average reductions (between room types) are 16.07 % and 4.07 %, respectively, showing a good correlation factor (0.85); in UL, these values are 26.04 % and 21.43 %, respectively, also showing a very good correlation factor (0.92). For Low Integrated buildings, the simulated and measured average reductions are 15.18 % and 6.38 %, respectively, with an almost perfect correlation factor of 0.99; in UL, these values are 23.13 % and -8.94 %, respectively, with an undesired correlation factor of -0.98. Summing all up, the simulated results show good correlation with the measured ones most of the times, being the model for Low Isolated buildings the poorest one and therefore the analyses need to be taken with caution. One should take into account that the measured throughput shows a great variability, either due to changes in TTI (UL), number of given codes (DL) or to instantaneous network load changes (DL/UL).

The correlation between throughput reduction and signal attenuation is shown in Table 4 for all building types, through (18). These results were obtained using a trend line for each building type. The simulated results show very good correlation coefficients (> 0.97), whereas the measured ones show poor correlation, particularly in UL (0.46), due to the reasons stated earlier.

### Table III. Model Parameters for the Signal Attenuation Due to Building Penetration

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Room Type</th>
<th>Indoor Window</th>
<th>Indoor Daylight</th>
<th>Deep Indoor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µ_In [dB]</td>
<td>µ_Dl [dB]</td>
<td>µ_De [dB]</td>
<td>σ_In [dB]</td>
</tr>
<tr>
<td>HInt</td>
<td>-2.37</td>
<td>15.19</td>
<td>9.4</td>
<td>-2.89</td>
</tr>
<tr>
<td>HIsol</td>
<td>-0.56</td>
<td>4.55</td>
<td>15.7</td>
<td>0.92</td>
</tr>
<tr>
<td>LInt</td>
<td>-1.98</td>
<td>13.79</td>
<td>5.2</td>
<td>-4.42</td>
</tr>
<tr>
<td>LIsol</td>
<td>-0.94</td>
<td>11.62</td>
<td>11.2</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

### Table IV. Correlation Between Throughput Reduction and Signal Attenuation for All Building Types.

<table>
<thead>
<tr>
<th>Building Type</th>
<th>Simulated</th>
<th>Measured</th>
<th>Simulated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ψ [dB·%]</td>
<td>ψ [dB·%]</td>
<td>ψ [dB·%]</td>
<td>ψ [dB·%]</td>
</tr>
<tr>
<td>HInt</td>
<td>3.20</td>
<td>13.33</td>
<td>3.06</td>
<td>0.98</td>
</tr>
<tr>
<td>HIsol</td>
<td>3.53</td>
<td>0.98</td>
<td>3.06</td>
<td>0.81</td>
</tr>
<tr>
<td>LInt</td>
<td>5.53</td>
<td>2.35</td>
<td>5.13</td>
<td>1.70</td>
</tr>
<tr>
<td>LIsol</td>
<td>3.83</td>
<td>4.61</td>
<td>5.13</td>
<td>1.70</td>
</tr>
</tbody>
</table>

2) Urban Scenarios Simulations

The reference scenario was studied thoroughly, in which different analyses were performed, such as the throughput reduction per floor and per room, and also the average reduction per floor transition and the total average reduction, independently of the building or room type.

In the DL floor analysis, shown in Fig. 4, Integrated buildings have the greatest throughput reduction in lower floors, reaching 78.30 % in High and 75.98 % in Low buildings; with the floor height increase, the trend is to increase throughput, up to 22.85 % for Low and -1.71 % for High buildings. One should notice that high ones even reach negative reduction, i.e., throughput gains in the upper floors, due to the exposure to higher signal power. In Integrated buildings, the trend is the opposite, since the interference reduces the available SINR: reductions are between 44.85 % and 51.24 % for Low buildings and between 25.26 % and 93.06 % for High ones.

In UL, shown in Fig. 5, the interference power is not so influencing therefore all trends are towards lower throughput reductions, those being comprehended between 96.64 % and -9.40 % for High Integrated, 49.27 % and 6.57 % for High Isolated, 93.23 % and 16.31 % for Low Integrated and between 69.83 % and 63.14 %. The latter case shows a very low
reduction with increase of floor height, which might be due to the low number of measured floors.

The average throughput reduction trend lines for the simulated building floors are presented in [17], as well as the correlation coefficients for each pair of curves.

The room analysis was also performed, showing increasing throughput reductions the inner the room is, Fig. 6. Contrarily to the measurement comparison, in this analysis, the goal is to identify the absolute reduction values and not the trend. In DL, results show higher average reductions in Isolated buildings (due to interference). For Integrated buildings, one can notice the influence of upper floors of HInt in lowering its average reduction. Regarding UL, the interference is not so evident, and the most influencing factor starts to be the signal received in the High buildings upper floors, lowering their average reduction.

Also interesting is the computation of the average reduction per floor transition, enabling the quantification of the floor height gain in terms of throughput, Table 5. The lower transmitting power and the shorter throughput range increase the UL throughput reduction in comparison to the DL case.

The parameters stated earlier were changed one by one, in order to understand their influence in the global output. The first parameter to be changed was the BS configuration relatively to the MT, as proposed in [5]. Two distinct parts were split, since the purpose of the analysis is different: in the first, the first 3 cases are analysed, where only the BS antenna position changes relatively to the MT, the distance between the BS and MT buildings being left unchanged (less than 20 m); in the second part, three distances were tested (30, 120 and 250 m) with the same BS configuration.

For the cases where the distance is lower than 20 m, Fig. 7, throughput reductions are lower in LoS cases (with the antenna on the roof-top of the adjacent building and the antenna on that building’s façade), resulting in an average reduction of 13.99% and 0.03% in DL and 1.96% and 0.03% in UL, respectively. The higher result for the rooftop antenna in DL is explained by the reduction caused by interference in Isolated buildings, whereas this effect is not present in the façade antenna since the distance to MT is lower. One should take into consideration that, at such short distance, SINR is high enough to assure the highest possible throughput, the influence of indoor signal attenuation being too low in the obtained throughput. In NLoS case, the opposite behaviour is found: due to the obstruction of the Fresnel ellipsoid, SINR suffers a great outdoor loss, resulting in great throughput reductions of 75.96% in DL and 92.35% in UL.

Regarding the distance variation, Fig. 8, the three tested distances include one LoS case (30m) and two NLoS cases (120 m and 250 m). In all building types, throughput reduction is higher when distance increases. In DL, throughput reductions are almost independent of the building type, with the exception of High Integrated, where interference is lower than in Isolated, and the building height makes the average lower due to the upper floors. Still, the average reduction is 22.13 %, 46.73% and 64.35% for 30 m, 120 m and 250 m, respectively. In UL, the effect of interference fades away (and so High Isolated buildings have the lowest reduction), leaving the major cause of reduction the low height of the buildings and therefore poor LoS conditions. In this link, the average

![Figure 4. Average DL throughput reduction along all simulated building floors.](image)

![Figure 5. Average UL throughput reduction along all simulated building floors.](image)

![Figure 6. Average throughput reduction for all simulated room types.](image)

### Table V. Average Difference of Throughput Reduction Between Floors.

<table>
<thead>
<tr>
<th>Room Type</th>
<th>$\Delta R_{floor}^{DL}$ (%)</th>
<th>$\Delta R_{floor}^{UL}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor Window</td>
<td>-1.43</td>
<td>-8.22</td>
</tr>
<tr>
<td>Indoor Daylight</td>
<td>-3.13</td>
<td>-9.18</td>
</tr>
<tr>
<td>Deep Indoor</td>
<td>-5.20</td>
<td>-9.55</td>
</tr>
<tr>
<td>Average</td>
<td>-3.25</td>
<td>-8.99</td>
</tr>
</tbody>
</table>

![Figure 7. Average DL throughput reduction along all simulated building floors.](image)

![Figure 8. Average UL throughput reduction along all simulated building floors.](image)
Reduction is 34.94 %, 48.57 % and 63.17 % for 30 m, 120 m and 250 m, respectively.

Regarding coverage analysis, Fig. 9, results show that a greater building coverage requires a greater throughput reduction. In both DL and UL, Isolated buildings show greater attenuations for 90 % and 95 % building coverage due to the greater standard deviations in the signal attenuation models, resulting in low throughput values. The exception to these great throughput reductions (between 80 % and 100 %) is the High Integrated case, which shows reduction below 80 % due to the absence of a great interference power level, particularly in DL.

The last analysis is the capacity one, using the developed Multi-User model. Both DL and UL were tested, assuming UL requests are made from the same users that require DL capabilities. Four distances were tested, using 18 m, 30 m, 120 m and 250 m in order to understand the user reduction in each case. For lower throughputs, the number of served users is limited by the number of available HSPA+ DL codes (15 codes available for data transmission), whereas for medium and higher throughputs, the limitation factors are the available signal power and interference level in the network. Fig. 10 for DL and Fig. 11 for UL show the user reduction in the outdoor to indoor transition for each throughput value. The low user reduction values are explained by the diversity of simulated scenarios: most of the cases show a throughput reduction, although some of them show an increase of throughput compared to the outdoor environment, particularly in High buildings.

IV. CONCLUSIONS

This paper addresses the study and quantification of the data rate transmission performance for a UMTS/HSPA+ system in indoor scenarios, giving special emphasis to capacity and coverage aspects. These goals were accomplished through the development and implementation of two models: the Single-User and the Multi-User one.

A measurement campaign was conducted to obtain a model for indoor signal attenuation, which was input in both Single and Multi-User models. Additionally, the measurements’ software provided information about the modulation usage in all measured sites. Generically, floor height gain is verified for all building types. High buildings show lower average building penetration attenuation due to the increase of signal availability.
in the upper floors (especially the Isolated case): 12.02 dB in HInt, 2.17 dB in HIso, 16.96 dB in LInt and 36.13 dB in LIso.

Regarding the comparison between measured and simulated results, the latter results show good correlation with the former most times. Signal attenuation can be correlated with throughput reduction, both in DL and UL. Increasing attenuation of 1 dB leads to average throughput reductions of 3.83 % in DL and 5.13 % in UL for simulation, and 4.61 % in DL and 1.70 % in UL for measurements.

The reference scenario was analysed in terms of floor and room penetrations. In DL, Integrated buildings have the greater throughput reduction in the lower floors. With the floor height increase, the trend is to increase the throughput. In UL, interference power is not so influencing therefore all trends are towards lower throughput reductions. Regarding the room penetration, the results show higher average reductions for DL in Isolated buildings (due to interference). For Integrated buildings, one can notice the influence of the HInt’s upper floors in lowering its average reduction. In UL, the interference is not so evident, and the most influencing factor starts to be the signal received in High buildings’ upper floors, lowering their average reduction. The floor height gain verified in terms of signal power is also present in the data rate, with an average data rate increase of 3.25 % in DL and 8.99 % in UL.

Variations to the reference scenario were analysed, mainly changing the distance to the BS and the desired building coverage. The distance analysis was performed for short (30 m), medium (120 m) and long (250 m) distances to the BS. Considering the short distance, the results show an average throughput reduction of 22.13 % in DL and 34.94 % in UL. For the medium and long distances, the DL and UL are roughly the same: reductions of 47 % and 64 % can be found, respectively. The coverage increase analysis shows high throughput reductions (between 80 % and 100 %) when the desired building coverage is high (90 % and 95 %). The exception to this are the High Integrated buildings, which show average reductions below 80 % due to the absence of a great interference power level, particularly in the DL.

The capacity analysis was performed using the developed Multi-User model. For lower throughputs, the number of served users is limited by the number of available HSPA+ DL codes, whereas for medium and higher throughputs, the limitation factors are the available signal power and interference level in the network. For shorter distances, the average user reduction concerning indoor penetration is lower than 1 %. For longer distances, such as 250 m, user reduction can rise up to 2.96 % in DL and 5.22 % in UL.

Summing up, in DL the most influencing factor is the presence of interference, lowering the average indoor throughput in Isolated buildings; in UL, the available signal is the key factor, in which higher buildings have greater average throughputs due to higher availability of signal in upper floors. Generically, data rate reductions are greater in UL due to the lower transmitting power and the shorter throughput range.

REFERENCES