Modelling of Linear Coverage in UMTS Applied to Tunnels and Bridges

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Abstract— The main purpose of this thesis was to study and analyse the coverage, the capacity and the interference in linear environments, such as the tunnels and the bridges. For this purpose, a model that accounts for different environmental and system parameters was developed and implemented in a simulator. For validation purposes, the results obtained in both scenarios were compared with measurements performed in a real network in the Lisbon Underground and in the 25 de Abril Bridge. Results show that, in tunnels, no coverage or capacity problems are expected, even considering a high number of users or the most demanding services, since the powers obtained are below the maximums allowed and the carrier-to-interference ratios are clearly above 0 dB for both DL and UL. In bridges, for the parameters considered, there might be some capacity problems since the maximum number of users served simultaneously is in the order of 15. Furthermore, if some of the users are performing the most demanding services, more capacity problems are expected. The developed model has proven to be very useful for radio planning in UMTS, since, in general, a good agreement was obtained with the measurements performed.

Keywords- UMTS, Coverage, Interference, Tunnels, Bridges.

I. INTRODUCTION

Mobile communications systems have experienced a rapid growth in the last decades, being essential nowadays, joining together communications and mobility.

Nowadays, users expect that good coverage exists wherever they are, thus, this is a key factor to maintain them satisfied. Therefore, since the performance of a mobile radio communication system depends on the radio propagation environment, besides the traditional urban, suburban and rural areas widely studied in the literature, a good coverage is also desired in other environments, such as the tunnels and the bridges. With the new and more demanding services, mobility is becoming more important and the number of users in trains and in cars is growing, thus, these cases must be carefully studied and analysed.

Tunnels and bridges have some common aspects. Both of them are linear environments where the planning is done considering that confined regions, thus the traditional COST231 – Okumura-Hata and the COST231 – Walfsch-Ikegami models [1] are not suitable for the propagation prediction since these models are used in outdoor environments and are not efficient to the study in linear environments. However, opposite to the tunnels case, in bridges the waveguide phenomenon is not present since they are open areas. In a bridge, a LoS condition between Base Station (BS) and the Mobile Terminal (MT) is normally observed and the reflections are mainly in the floor and due to other vehicles.

Railway and road tunnels are very common nowadays in metropolitan cities, therefore, radio coverage is needed for personal and emergency communications [2]. As a result, radio wave propagation in tunnels has been widely studied for years. A detailed study of the technical literature reveals that some work relevant to the problem has been published, namely some propagation models and experimental results mainly to describe the path loss behaviour, in [3], [4], [5], [6] and [7]; extensive references to other works are provided in all the mentioned works.

Wireless communications in a bridge are not extensively studied in the literature, although a good coverage is also required in this type of environment. The main reason should be that the free space propagation model provides a good approximation to the real behaviour of radio propagation in bridges; however, some characteristics, related to fading and to the existence or not of traffic, must be taken into account in order to optimise the system and the available resources.

As mentioned, the propagation models used in the environments being studied are more or less defined. However, although Universal Mobile Telecommunications System (UMTS) is already implemented in many parts of the world, a complete model, to study the path loss, the coverage, the capacity and the interference in such environments is needed in order to improve the radio network planning and optimisation. In fact, such a tool can be an important contribution to a more efficient exploitation of the resources available, allowing the companies operating in these areas to significantly reduce their costs with the equipments required in the networks and to maintain their clients satisfied, which is very important nowadays. It is well known that the design of wireless systems does not only aim to optimise performance
for specific application, but also to do that at reasonable cost [8].

The main purpose of this work is the study of coverage, capacity and interference in UMTS in linear environments, namely in tunnels and in bridges. These objectives were accomplished through the development and implementation of a complete model that allows the study of the propagation in both environments as well as the estimation of the parameters referred. The methods and the expressions used in the calculation of the parameters are presented. The study of these parameters in different scenarios, varying, e.g., the environmental characteristics, the number of users and the services used, is performed. The characteristics of the scenarios were carefully chosen to approximate the environments to the real tunnels and bridges studied. The results obtained with the simulator are compared with the measurements performed in the real network, in order to validate and evaluate the simulator. Measurements have been conducted in the Lisbon Underground and in the 25 de Abril Bridge.

In Section II the models for the theoretical calculations of the path loss in tunnels and in bridges are described, as well as the interference models used. The default scenarios, the results for some parameters variation as well as the results obtained in the measurements are presented and analysed in Section III. In Section IV the main conclusions are drawn.

II. THEORETICAL MODELS

A. Propagation in Tunnels

The propagation of electromagnetic waves in tunnels can not be studied as in other environments. Considering the tunnel as a waveguide and since the cross-sectional dimensions in tunnels are, normally, large compared to the wavelength, as happens in UMTS, the propagation is strongly multi-modal, [3]. There are several factors that influence radio coverage in a tunnel, such as the frequency used, the tunnel section, the existence of curves, some characteristics of the walls, and also characteristics of the antennas.

Since coverage, capacity and interference are the main parameters being studied in this work, it is important to have a good estimation of the path loss observed in a tunnel. The model used and described in the next paragraphs is based in [7], since it was successfully tested in many tunnels, being also used and referenced by other authors.

In this model, two regions are considered: near and far ones. In the near region the propagation loss is larger due to the interaction of many modes and the propagation takes place as if it were in free space, being approximated by a single ray optical model as

\[ L_{nr}[\text{dB}] = 5 \alpha d \left[ \log_{10} \left( \frac{1}{f \lambda^2} \right) + \frac{1}{2} \log_{10} \left( \frac{1}{f \lambda^2} \right) \right] + \] (2)

where \(w\) and \(h\) are respectively the width and the height of the tunnel, \(\Gamma_{12}\) are the reflection coefficients of the vertical/horizontal walls, obtained with the Fresnel formulas, and \(L_{\text{asec}}, L_{\text{asinc}}\) are the coupling losses of the transmitting/receiving antennas. The antenna coupling loss depends on the near-field characteristics of the antenna, and can be measured in the laboratory or obtained as [6]

\[ L_{\text{asec}}, L_{\text{asinc}}[\text{dB}] = 10 \log_{10} \left( \frac{2 \pi h w}{\lambda G_{t,r}} \cos \frac{\pi x_{t,r}}{w} \cos \frac{\pi y_{t,r}}{h} \right) \] (3)

where \(x_{t,r}\) and \(y_{t,r}\) are the positions of the transmitter/receiver antenna in the \(x\) and in the \(y\) axis, respectively, according to the coordinate system defined in Fig. 1, with the origin at the centre of the tunnel.

![Figure 1. Representation of the tunnel section.](image)

Normally, tunnels have two different section types: rectangular and circular; however the model can be applied for any tunnel shape. For rectangular tunnels, the dimensions considered are the width \(w\) and the height \(h\) of the tunnel. For circular or other-shaped tunnels, an equivalent rectangular section is obtained as follows: the cross-sectional area of the equivalent rectangular tunnel is the cross-sectional area of the circular tunnel and the width of the equivalent rectangular tunnel is the floor width of the circular tunnel [7]. This way, the width and the height of the equivalent rectangular tunnel are obtained and the analysis is done considering this equivalent tunnel.

The separation between the near and the far regions is defined by the break point, which can be obtained as the intersection of both models’ curves, where the propagation losses are equal.

Another factor that contributes to attenuate the signal is the presence of curves. To account for this factor, shooting and bouncing ray method is used based in [3] and [6]. This attenuation is obtained as the average of the losses suffered by all the rays, at a certain distance \(z\)’. The attenuation depends on the length of the curve, on the reflection coefficient and on the roughness of the walls.
The received signal inside a vehicle or train, which is the case inside tunnels, is lower in comparison with an outdoor use. Since there is the need to provide reliable in-vehicle coverage, it is necessary to consider the vehicle or train penetration loss.

Presented the model, it is possible to conclude that it is easy to use and, according to the experiments shown in [6], accurate enough to predict the propagation attenuation in a tunnel.

B. Propagation in Bridges

The propagation models used to predict the path loss in a bridge are here presented.

When there are many vehicles on the bridge the free space propagation model is used to calculate the propagation loss between the MT and the BS. This model is, in this case, a good approach due to the LoS condition usually verified and due to the obstruction, caused by the vehicles on the bridge, of the reflected ray in the soil not allowing the usage of the flat earth propagation model. Additionally, fast fading must be taken into account due to the changes in the environment caused especially by the movements of other vehicles, with a Rice distribution due to the LoS condition, while the log-normal distribution is used to account for the slow fading [1].

For the case of inexistence of traffic, the flat earth propagation model, described in [1], is used, since a direct and a reflected ray are present. This model gives good results for short distances, and considers that there is LoS between the MT and the BS. These conditions are suitable for the propagation in bridges, since the distance between the BS and the MT is normally short enough to allow the consideration of a flat earth situation and normally a LoS condition is observed. In what concerns to fading, fast fading with Rice distribution and slow fading with log-normal distribution are considered. However, this model has some limitations, in the sense that it is valid for distances between the BS and the MT satisfying

\[ d > \frac{5kh_{h}h_{mt}}{\pi} \]  

where \( h_{h} \) and \( h_{mt} \) are respectively the heights of the BS and of the MT and \( k \) is the propagation constant. Due to this restriction, when there is no traffic in the bridge, first the free space propagation model is applied up to that minimum distance, then, from the distance from which the free space propagation loss is equal to the flat earth propagation loss, the flat earth model is used. This way, it is guaranteed that there are no discontinuities in the attenuation curve. It is important to note that it has been verified analytically that the intersection of both curves occurs always after the minimum distance of application of the flat earth propagation model.

The propagation attenuation in free space is given by [1]

\[ L_{p[an]} = 32.44 + 20 \log(d_{an}) + 20 \log\left(\frac{f_{an}}{f_{0}}\right) \]  

while for flat earth the expression used is [1]

\[ L_{s[an]} = 120 - 20 \log\left(\frac{f_{an}}{f_{0}}\right) - 20 \log\left(\frac{h_{an}}{h_{mt}}\right) + 40 \log\left(\frac{d_{an}}{d_{mt}}\right) \]  

The heights of the MT, since MTs are inside vehicles, depend on the type of vehicle considered, the height of 1 m being a typical value for cars. The additional loss due to vehicles is also considered for propagation in bridges.

C. Interference Models

Interference is present in every mobile cellular communications systems. Since Wideband Code Division Multiple Access (WCDMA) systems are interference-limited, the interference study is fundamental in UMTS. The total interference experienced by an MT is composed of two parts: the intra- and the inter-cells [9]. In the Downlink (DL) case, the intra-cell interference is caused by the BS on a MT due to partial loss of orthogonality, caused by multipath, between the codes used for users in the same cell. The inter-cell interference, in DL, is caused by the power received by the MT from the BSs located in adjacent cells. In the Uplink (UL) case, the intra-cell interference in the BS is caused by all the other MTs served by the same BS, while the inter-cell interference is due to the signals received from MTs from the adjacent cells.

There are several models in the literature for the calculation of the interference, with different parameters and considerations, some of them mentioned in [10]. In this work, the interference models used are based in [10]. For DL, the total power transmitted by the BS, the orthogonality factor and the propagation losses between BS and MT are considered in the models adapted, while for UL, the number of users, the received signal power and the activity factor, according to the user’s service, are considered, as well as perfect power control [10].

The intra-cell interference in DL, for MT \( i \), is given by

\[ I_{\text{intra, DL}}[W] = \left( P_{TX}^{t} \cdot P_{BS \rightarrow MT}^{u} \right) \times \alpha \times L_{p} \]  

where \( P_{BS \rightarrow MT}^{u} \) is the power received by the BS to the MT in which interference is being calculated, \( \alpha \) is the orthogonality factor, and \( L_{p} \) is the path loss between the BS and the MT in which interference is being calculated.

The intra-cell interference in UL can be obtained as

\[ I_{\text{intra, UL}}[W] = \sum_{j=1}^{N_{BS}} P_{BS \rightarrow MT}^{u} \times v_{g} \times N_{s} \]  

where \( P_{BS \rightarrow MT}^{u} \) is the power received in the BS \( j \) from an MT, \( v_{g} \) is the activity factor of service \( g \), \( N_{s} \) is the number of MTs using service \( g \) on the cell of BS \( j \) and \( N_{s} \) is the total number of services used.

The inter-cell interference, in DL, in an MT \( i \), can be obtained as

\[ I_{\text{inter, DL}}[W] = P_{TX}^{u} \sum_{j=1}^{N_{BS}} P_{BS \rightarrow MT}^{u} \times \alpha \times L_{p} \]  

where \( P_{TX}^{u} \) is the BS \( j \) total transmitted power including antenna gain and \( N_{BS} \) is the number of interfering BSs.

The inter-cell interference in UL is given by
\[ I_{UL}^{\text{IR}} = \sum_{n=1}^{N_{\text{MT}}} \sum_{j=1}^{N_{\text{BS}}} P_{j,n} \times r_{n,j} \times A; \tag{10} \]

where, for the tunnel case, the \( A \) parameter is given by
\[ A = \sum_{n=1}^{N_{\text{MT}}} 10^{\frac{[\nu_n + 10 \log_{10} (\frac{1}{\lambda})] + 10 \log_{10} \left( \frac{1}{\Gamma_1} \right)}{10} r_{n,j} \times A; \tag{11} \]

while for the bridge it is obtained as
\[ A = \sum_{n=1}^{N_{\text{MT}}} 10^{\frac{[\nu_n + 10 \log_{10} (\frac{1}{\lambda})] + 10 \log_{10} \left( \frac{1}{\Gamma_1} \right)}{10} r_{n,j} \times A; \tag{12} \]

where \( N_{\text{users}} \) is the number of users in the sector studied and in the interfering sectors, \( P_{j,n} \) is the BS \( j \) received power from MT \( n \) being covered by an adjacent cell \( q \), \( r_{n,j} \) is the distance from MT \( n \) using service \( g \) to interfering BS \( q \), \( r_{n,j} \) is the distance from MT \( n \) using service \( g \) to BS \( j \) and \( N_{n,g} \) is the number of users using service \( g \) in the interfering cell \( q \).

### III. RESULTS ANALYSIS

#### A. Scenarios

In order to evaluate the coverage, the capacity and the interference in the tunnel and in the bridge, a default scenario was conceived for each case.

The main parameters considered in the default scenario for the tunnel case are presented in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tunnel width [m]</th>
<th>Tunnel height [m]</th>
<th>Permittivity</th>
<th>Number of users</th>
<th>Sector range [m]</th>
<th>MT distances to the BS [m]</th>
<th>BS position (x,y) [m]</th>
<th>MT position (x,y) [m]</th>
<th>Other MTs positions</th>
<th>Indoor penetration attenuation [dB]</th>
<th>Rician K parameter [dB]</th>
<th>Gaussian standard deviation [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>6</td>
<td>5</td>
<td>25</td>
<td>500</td>
<td>50, 100, 200, 300, 400, 500</td>
<td>(0,1)</td>
<td>(2,-1)</td>
<td>Random</td>
<td>9</td>
<td>1.5</td>
<td>4</td>
</tr>
</tbody>
</table>

Regarding the bridge, the values presented in Table II were carefully chosen to represent a normal scenario in a bridge. In this case, a non traffic situation is considered.

The frequencies, the noise figure, the user and cable losses and the signalling and control parameters are also typical values used in UMTS, presented in Table III.

For the interference analysis, for both cases, four interfering BSs are considered, being two at 1 km from the BS studied, one in each direction, and two at 2 km, being one in each direction.

#### TABLE II. DEFAULT SCENARIO FOR THE BRIDGE CASE.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bridge width [m]</th>
<th>BS position (x) [m]</th>
<th>BS height [m]</th>
<th>MT position (x) [m]</th>
<th>Number of users</th>
<th>Sector range [m]</th>
<th>Distances of the MT to the BS [m]</th>
<th>Number of users</th>
<th>Sector range [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22</td>
<td>0</td>
<td>5</td>
<td>6</td>
<td>15</td>
<td>500</td>
<td>50, 100, 200, 300, 400, 500</td>
<td>15</td>
<td>500</td>
</tr>
</tbody>
</table>

#### TABLE III. DEFAULT PARAMETERS FOR THE LINK BUDGET.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Frequency [MHz]</th>
<th>Noise Figure [dB]</th>
<th>Signalling and control power [%]</th>
<th>BS radiation pattern</th>
<th>MT antenna gain [dBi]</th>
<th>User losses [dB]</th>
<th>Cable losses [dB]</th>
<th>Service</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2110</td>
<td>8</td>
<td>25</td>
<td>K742266</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>Voice (12.2 kbps)</td>
</tr>
</tbody>
</table>

#### TABLE IV. DEFAULT PARAMETERS FOR THE BRIDGE CASE.

### B. Results

#### 1) Tunnel Case

In this section, the results of the simulations performed for the tunnel case are presented and analysed. Additional results can be found in [11].

The BS transmitted power does not show significant variations when the user goes far from the BS. This is expected since there are 25 users covered by the BS, randomly generated in a 500 m range. The total power transmitted by the BS is distributed to all the users, meaning that if one user changes his position the total power is not much affected. The value of 16 dBm for this parameter (considering 25% additional signalling and control power) is acceptable since it is below the maximum transmission power allowed in a BS, which is about 43 dBm.

Regarding the UL case, the transmission power decreases from about 0.7 to -11 dBm when the distance increases from 50 to 500 m, as shown in Fig. 2. In fact, it was expected that the power would increase with the user distance, but this is not what happens. This fact is related to the radiation pattern of the BS antenna, since when the MT is at 50 m from the BS, in the x=2 m position, the receiving antenna gain is about 8.6 dBi, increasing with distance being of about 16.4 dBi at 500 m. Therefore, despite the increase in the path loss with distance, there is also an increase of the BS antenna gain, causing a decrease in the transmission power required in the...
MT when the user is far from the BS. Moreover, the path loss increase, when the MT goes from 50 to 500 m from the BS, is of about 2 dB due to the small propagation attenuation with distance verified in a tunnel after the break point, which is located at around 87 m in this case. For all the cases, powers are below the maximum transmission power allowed in the MT which is around 21 dBm.

In the cases studied so far, the BS is covering a 500 m length. An analysis for different ranges is also performed.

Regarding the BS transmission power, a decrease from 22 to 14 dBm is observed when the range increases from 100 to 900 m, due to the high directive BS antenna and to the decrease of the interference, since the interfering BSs are located at higher distances. In what concerns the MT transmission power, a decrease from 4.4 to -1.9 dBm is observed between the same ranges, the MT being at 50 m from the BS.

The influence of the services performed by different users is interesting to analyse. Figure 4 shows the variation of the BS transmission power for different services for the user studied and for other users, the user studied being at 50 m from the BS. It is possible to observe that, in general, the power increase when the user’s service becomes more demanding, decreasing when all other users are performing services with higher data rates. This behaviour is explained by the limitations in capacity, since, as the data rates increase, the number of served users decreases, thus, the power is lower.

The MT transmission power exhibits a similar behaviour, the power being between -10 and 12 dBm for all cases.

The influence of the BS antenna radiation pattern in the parameters studied is important to analyse, since significant changes can be observed with concerning coverage and capacity. A comparison is done between the antenna so far considered and an omnidirectional antenna with 15.3 dBi gain.

The BS transmission power increases 4 dB comparing with the default case. Regarding the MT transmission power, the variation with distance is presented in Fig. 5. In this case, no significant variations in the power, with distance, are observed, since the antenna gain is constant, the small increase with the distance being explained by a similar increase in the path loss. The power required in the MT is in most of the cases higher than that obtained in the default case, the difference for distances above 300 m being around 7 dB.

The variation of the results when there is a curve in the tunnel is also analysed. An increase of about 11 dB comparing with the default scenario was observed in the BS transmission power, caused by the increase in the path loss, in the interference and in the fast fading margin, since the Rayleigh distribution is used when an NLoS situation is observed. In what concerns the MT transmitted power, an increase between 11 and 13 dB is observed for all the considered distances, for the same reasons.
2) Bridge Case

Similar to the tunnel case, the default scenario for the bridge is also analysed, as well as some parameters variation, being additional results presented in [11].

The DL transmitted power exhibits an almost constant behaviour with the MT distance, which is expected, since the other 14 users in the sector are randomly generated, therefore, the position of a user, the one being studied, is not significant when 15 users are being covered. The values obtained for this parameter are around 31.1 dBm, thus, below the maximum transmitted power allowed in the BS, therefore, no coverage or capacity problems are expected.

In what concerns the MT transmission power, Fig. 6 shows the results obtained for each distance considered. When the distance increases from 50 to 500 m, it is possible to observe an increase on the power from about -13 to 19.4 dBm, thus, being below the maximum allowed.

The DL interference is between -115 and -95 dBm, while the UL one is around -100 dBm. For DL, C/I is around 14.5 dB, in UL being about 11.4 dB.

The variation of the number of users is also performed for the bridge. The BS transmission power varies from 10 to 50 dBm, being the lower power obtained for 5 users and the higher for 35. For 25 users, the power is 43 dBm, thus, the maximum allowed, therefore, being this approximately the capacity. Regarding the MT transmission power, the variation among 5 and 35 users is of 20 dB. For 25 and 35 users, the powers are above 21 dBm for some distances.

The BS transmission power increases with the range, from about 0 dBm for 100 m range to 40 dBm for 900 m range. The increase of interference, path loss, and the tilt considered in the BS antenna, are the main reasons for this behaviour.

The variation of the MT transmission power is presented in Fig. 7. A decrease of about 11 dB is observed between the 100 and the 500 m ranges, for the same reasons previously mentioned. For higher distances, the results are different, due to the behaviour of the interference.

Similar to the tunnel, the influence of the data rates’ variation is studied in the bridge. The BS transmission power varies from 6 to 48 dBm, being above the maximum when the user is performing the most demanding service and the other users with 12.2 or 64 kbps. The limitations in capacity, as in the tunnel, are important, since the number of users decreases when the services are more demanding.

Regarding the MT transmission power, variations between -23 and 3 dBm are observed.

Since there are changes in the environment, namely, in this case, the variation of the number of cars in the bridge, it is important to analyse the variation in the results when other values for the K parameter are considered.

The variation of the BS transmission power with the K parameter, for the user at 200 m, is presented in Fig. 8. This variation is only presented for one distance, since the power does not show significant variations with distance. As expected, the transmission power decreases when the K parameter increases, since it corresponds to a clearer LoS condition due to the lower movements in the environment. This decrease is in the order of 22 dB, between the extreme cases considered, i.e., among K=0 dB and K=19 dB.
A comparison is also done for the cases with and without traffic. The power transmitted by the BS increases about 0.5 dB when traffic is considered. In what concerns the MT transmission power, the same situation is observed. Since the BS range is 500 m, the cases with and without traffic are very similar due to the location of the break point, 442 m, which is close to 500 m.

C. Measurements Results

1) Lisbon Underground

In order to evaluate the simulator, some measurements were performed in two tracks of the Lisbon Underground, including 18 stations. The tracks between Intendent and Alameda, Campo Pequeno and Saldanha, and Picoas and Marquês de Pombal were considered. Among the tracks studied, it is observed that no handovers are performed, thus, a comparison with the simulations can be done, since the simulator analysis is done for one BS.

Regarding the position of the MT in the carriage, it is the same for all cases, being of about $x = 1$ m and $y = 0$ m. In what concerns the BS position, it was considered at $x = 3.5$ m and $y = 1$ m, however, this is an assumption, since no information was obtained for these values. The number of users in the ranges mentioned had to be estimated. Noting the observations done on the surrounding environment during the measurements and the distances considered, 15 users were chosen for all cases.

The first case studied is the track between Intendente and Alameda. The power transmitted by the MT obtained in measurements and in simulations is presented in Fig. 9. It should be noted that, since the speed of the train is not known, the distances presented can be different than the real distances between the BS and the MT.

The general behaviour of the transmitted power is predicted by the model, the average difference between measurements and simulations being about 6.5 dB, and the standard deviation around 5 dB. The rapid fluctuations of the power observed in the measurements are essentially due to the changes in the environment, e.g., people moving in the train, and due to the variations on the speed of the train. It is possible to note that no significant variations are observed in the power predicted by the simulations, since the path loss decreases very slightly with the distance in a tunnel; furthermore, the BS antenna gain increases slightly when the distance increases, thus, the variations being negligible.

The received power obtained in the measurements and in the simulations, for the track considered, is presented in Fig. 10. It is possible to observe that in most of the cases the values obtained in the simulations are below the values measured. One of the reasons for this behaviour can be the fact that many assumptions are taken in this study, as the BSs positions, the number of users served and the fading parameters. In this case, the average difference between measurements and simulations is about 10.7 dB, the standard deviation being 7 dB.

The received power obtained in the measurements and in the simulations, for the track considered, is presented in Fig. 10. It is possible to observe that in most of the cases the values obtained in the simulations are below the values measured. One of the reasons for this behaviour can be the fact that many assumptions are taken in this study, as the BSs positions, the number of users served and the fading parameters. In this case, the average difference between measurements and simulations is about 10.7 dB, the standard deviation being 7 dB.

Figure 10. Power received by the MT between Intendente and Alameda.

Figure 11 presents the power transmitted by the MT obtained in the measurements and the in the simulations, for the track between Campo Pequeno and Saldanha. Similar to the first track considered, the prediction generally follows the measurements, the average difference between both approaches being around 7.6 dB and the standard deviation about 7.4 dB. The fluctuations observed are caused by the same factors mentioned in the previous track.

The power transmitted by the MT obtained in the measurements and the in the simulations, for the track between Campo Pequeno and Saldanha. Similar to the first track considered, the prediction generally follows the measurements, the average difference between both approaches being around 7.6 dB and the standard deviation about 7.4 dB. The fluctuations observed are caused by the same factors mentioned in the previous track.

Figure 11. Power transmitted by the MT between Campo Pequeno and Saldanha.

Regarding the third track, between Picoas and Marquês de Pombal, the powers transmitted by the MT obtained in the measurements and predicted by the simulations are presented in Fig. 13. In general, the behaviour of the transmitted power is predicted by the simulations, the average difference between measurements and simulations being around 5.4 dB, while the standard deviation is 4.4 dB. The fluctuations observed are caused by the previously mentioned factors, not predicted by the model.
Figure 12. Power received by the MT between Campo Pequeno and Saldanha.

Figure 13. Power transmitted by the MT between Picoas and Marquês de Pombal.

The received power obtained for this track, for both measurements and simulations, is presented in Fig. 14. A reasonable agreement is obtained between measurements and simulations, the average difference between both approaches being around 5.9 dB, and the standard deviation about 4.7 dB.

Figure 14. Power received by the MT between Picoas and Marquês de Pombal.

The situation of two trains passing inside the tunnel simultaneously was observed in some tracks, however, no particular variation was detected in the powers. Since both powers show significant variations along the tunnel, no conclusion can be taken regarding the influence of the obstruction caused by the other train.

2) 25 de Abril Bridge

Regarding the bridge, the 25 de Abril Bridge was the one chosen to do the measurements, since it has UMTS coverage and it is one of the main bridges in the city of Lisbon.

During the measurements, the speed of the car was almost constant, being of about 40 km/h, in order to reduce the speed influence in the results, enabling a better analysis of the results. In fact, since the simulator uses a snapshot approach, the speed of the MT is not considered.

The results were analysed in order to perform simulations in similar conditions as those observed during the measurements.

The BS is located at 8 m height, at approximately $x=0$ m, and has a down tilt of 2°. One assumption that had to be taken is the number of users considered, since it is not possible to know this parameter. A 900 m range being studied, and since a traffic situation is observed, 10 users is a reasonable number to be considered.

The results concerning the MT transmission power for the measurements and for the simulations are presented in Fig. 15. It is possible to observe a very good agreement between the measurements and simulations, the average difference between measurements and simulations being around 4 dB, the standard deviation being 2.9 dB. The variations of the transmitted power in measurements are essentially caused by the changes in the environment, such as passing cars or trucks close to the MT and by the variation of the number of active users; however, the behaviour of the curves and the values obtained for both cases are very similar. The increase of power with distance is essentially caused by the increase in path loss.

Figure 15. Power transmitted by the MT in the 25 de Abril Bridge.

In what concerns the MT received power, the results for both cases are presented in Fig. 16. In this case, the differences between measurements and simulations are more significant, varying between 7 and 20 dB, although for most of the cases being of about 10 dB. The average difference is about 14 dB, while the standard deviation is 4.4 dB. However, a good agreement in the behaviour of both curves is observed, especially for distances above 200 m.

Figure 16. Power received by the MT in the 25 de Abril Bridge.

The differences can be explained by some of the assumptions taken in the simulations. One of them is, as mentioned, the distances considered for the interfering BSs.
This is an important aspect in the sense that it influences the interference which is used for the calculation of the receiver sensitivity. Furthermore, in the simulations, the characteristics of the interfering BSs, namely their height and their tilt, is considered equal to that defined for the BS studied, this approximation being possibly one of the reasons for the differences observed between the measurements and the simulations. Another assumption taken in this analysis is the number of users considered. In fact, a variation in this number also causes a variation in the interference, thus, in the received power. Moreover, the fading parameters considered can also be different than those present during the measurements. In fact, the $K$ parameter, used to describe the fast fading, can cause significant changes in the results obtained.

IV. CONCLUSIONS

The main objectives of this work were to study the propagation, coverage, capacity and interference in linear environments, namely in tunnels and bridges, in UMTS, thus the study of a useful practical application. These goals were achieved through the development and implementation of a simulator, which accounts for many parameters that can influence this analysis in such environments, providing the application wished. In the tunnel, the propagation model used is presented in [7]. For the bridge, the free space and flat earth propagation models are considered.

Concerning the tunnel, it is observed that the path loss is lower in comparison with other environments due to the waveguide phenomenon, confirming the theoretical expectations. Both BS and MT transmission powers, for the default case, are below the maximum allowed, $C/I$ for DL being in the order of 13 dB, and about 10.5 dB for UL.

The increase in the tunnel dimensions leads to an increase in both DL and UL transmitted powers, since the location of the break point is highly related with these parameters. In fact, the larger the tunnel dimension is, the further the location of the break point is from the transmitting antenna, due to the reduction of the waveguide phenomenon.

In what concerns the influence of the number of users, it is observed that, as expected, the powers increase when more users are active, however, even with 35 users, the powers are below the maximum.

A study is also performed to evaluate the influence of the variation of the BS range. The transmission powers decrease when the range increases from 100 to 900 m. This study is important when the planning or optimisation of a network is being performed, since the distances between the BSs must be carefully chosen to improve the coverage and the capacity of the system.

The influence of the variation of the data rates is also studied, since a 3rd generation system is being analysed. In this case, significant variations in the transmitted powers and in capacity are observed.

The variation of the BS antenna radiation pattern is also analysed, since this is an important parameter in system planning and optimisation. In fact, the radiation pattern influences strongly the results obtained concerning coverage and capacity. A directive antenna is more efficient than an omnidirectional antenna, in tunnels, since the required power in both BS and MT is lower, thus, increasing coverage and capacity.

The influence of a curve in the tunnel is also studied. When a curve is considered, an increase of about 11 dB is observed in the BS transmission power, a similar behaviour being observed for the MT transmission power.

Concerning the bridge, for the default scenario, the power in DL is around 31 dBm, in UL being between -13 and 19.4 dBm. In what concerns $C/I$, the values obtained are of about 14.5 and 11.4 dB for DL and UL respectively.

Concerning the number of users, it is concluded that with 15 users no coverage problems are expected and, as the number of users increase, the analysis must be carefully done, in order to estimate capacity.

Regarding the BS range, significant variations are observed in both BS and MT transmission powers, however, both being below the maximum allowed.

In what concerns the services performed, in some cases, it is observed that the BS transmission power is above the maximum, namely, for the cases where the user is performing the most demanding data service, while the other users are performing voice or 64 kbps, therefore, some coverage and capacity problems are expected.

To simulate the variation of the number of cars in the bridge, the $K$ parameter of the Rice distribution is varied. In this case, significant variations are observed in the powers. In this case, the MT cannot communicate with the BS for distances above 300 m, if $K=0$ dB, since at this distance the power is about 20 dBm, thus, closer to the maximum.

Concerning the traffic situation, no significant variations are observed in the powers, due to location of the break point.

The measurements performed in the Lisbon Underground show that, in general, a good agreement is obtained with the results predicted by the model, for the MT transmitted and received powers, the variations being explained by some of the assumptions taken in the simulations.

Regarding the measurements performed in the 25 de Abril Bridge, a very good agreement is achieved in what concerns the MT transmission power. In what concerns the power received, the average difference between measurements and simulations is around 14 dB. This behaviour can be explained by the fact that some assumptions are taken in the simulations which, probably, need to be more carefully considered, such as the number of users, and the number and position of interfering BSs.

REFERENCES


