Modelling of Linear Coverage in UMTS Applied to Tunnels and Bridges

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***Abstract* — This paper addresses the study of coverage, capacity and interference of UMTS in tunnels and bridges. For this purpose, a model accounting for several parameters was developed and implemented in a simulator. The results were compared with measurements performed in the Lisbon Underground and in the *25 de Abril* Bridge. Results show that, in tunnels, no coverage or capacity problems are expected. On the other hand, in bridges, for the parameters considered, there might be some capacity problems. The model has proven to be very useful for radio planning, since, in general, a good agreement was obtained with the measurements.**

I. INTRODUCTION

Mobile communications systems have experienced a rapid growth in the last decades, being essential nowadays, joining together communications and mobility. Since the performance of a mobile communications 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 cars is growing, thus, these cases must be carefully studied.

Tunnels and bridges have some common aspects. Both linear environments, where planning is done considering them as confined regions, thus, the traditional COST231 – Okumura-Hata and the COST231 – Walfisch-Ikegami models [1] are not suitable for path loss prediction. However, opposite to tunnels, in bridges the waveguide phenomenon is not present, since they are open areas. In a bridge, an LoS (Line-of-Sight) condition between Base Station (BS) and Mobile Terminal (MT) is normally observed and reflections are mainly on the ground and due to other vehicles.

Radio wave propagation in tunnels has been widely studied for years. A study of the literature reveals that work has been published on propagation models and experimental results, mainly to describe the path loss behaviour, [2], [3], [4], [5] and [6]; extensive references to other works are provided in all these references.

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 may 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 the existence, or not, of traffic must be taken into account.

Although Universal Mobile Telecommunications System (UMTS) is already widely deployed, a complete model to study the path loss, coverage, capacity and interference in such environments is steel needed. In fact, such a tool can be an important contribution to a more efficient exploitation of the resources available, allowing companies operating in these areas to significantly reduce their costs with the required equipments and to maintain the desired QoS (Quality of Service).

The main purpose of this work is the study of coverage, capacity and interference in UMTS in tunnels and in bridges. These objectives were accomplished through the development and implementation of a complete model that allows the study of propagation in both environments. The methods and models used in the calculation of the parameters are presented. The study of the relevant parameters in different scenarios is performed. The results obtained with the simulator are compared with 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 are described, as well as the interference models. The main 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

Wave propagation in tunnels cannot be studied as in other environments. Considering the tunnel as a waveguide, and since the cross-section dimensions in tunnels are large compared to the wavelength (for the usual mobile communication systems), propagation is strongly multi-modal, [2].

Since coverage, capacity and interference are the main parameters being studied, it is important to have a good estimation of the path loss observed in a tunnel. The used model is based on [6], since it was successfully tested in many tunnels, being used and referenced by other authors.

In this model, two regions are considered: near and far ones. In the near region, propagation loss is larger due to the interaction of many modes, and propagation takes place as if it were in Free Space.

In the far region, the attenuation increase with distance is smaller, since it can be assumed that only one mode is propagating. Propagation takes place as if it were in a waveguide, the analytical Optical Ray model being used, resulting for the path loss

$$L_{fr\ [\mathrm{dB}]} = 5\lambda d\left[\left(1/w^2\right)\log_{10}\left(1/\Gamma_1^2\right)+\left(1/h^2\right)\log_{10}\left(1/\Gamma_2^2\right)\right]+ \\ +L_{ant\ t[\mathrm{dB}]}+L_{ant\ r[\mathrm{dB}]} \quad (1)$$

where λ is the wavelength, d is the distance between BS and MT, w and h are, respectively the width and height of the tunnel, $\Gamma_{1,2}$ are the reflection coefficients of the vertical/horizontal walls (obtained with the well known Fresnel expression), and $L_{ant\ t,r}$ are the coupling losses of the transmitting/receiving antennas.

The conditions for the model's application, as well as its details, are described in [7].

B. Propagation in Bridges

When there are many vehicles in a bridge, the Free Space propagation model is used to calculate the path loss between MT and 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 on the ground, not allowing for the usage of the Flat Earth propagation model.

For the case of inexistence of traffic, the Flat Earth propagation model, [1], is used, since a direct and a reflected rays are present. This model gives good results for short distances, and considers LoS between MT and BS.

Detailed information regarding the application of these models can be found in [7].

C. Interference Models

Interference is present in every mobile cellular communications system. Since Code Division Multiple Access (CDMA) systems are strongly interference-limited, interference study is fundamental in UMTS. There are several models in the literature for the calculation of interference, with different parameters and considerations, some of them mentioned in [8], which are taken in this work. For DL (Downlink), 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 (Uplink), 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.

The considerations taken and the expressions used in the models are detailed in [7].

III. RESULTS ANALYSIS

In order to evaluate coverage, capacity and interference in the tunnel and the bridge, and the respective parameters, a default scenario was conceived for each case. The main parameters considered in the default scenarios, as well as detailed results analysis, are presented in [7].

A. Tunnel Case

In this section, the results of the simulations performed for the tunnel case are presented and analysed.

Regarding the default scenario, the total required BS transmitted power does not show significant variations when the user goes far from the BS, which is expected. The value of 16 dBm obtained for this parameter (considering 25 % additional signalling and control power) is acceptable, since it is below the maximum allowed, which is 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. 1. This fact is related to the low propagation attenuation verified in a tunnel, and to the radiation pattern of the BS antenna. For all the cases, transmission powers are below the maximum allowed in the MT, which is 21 dBm.

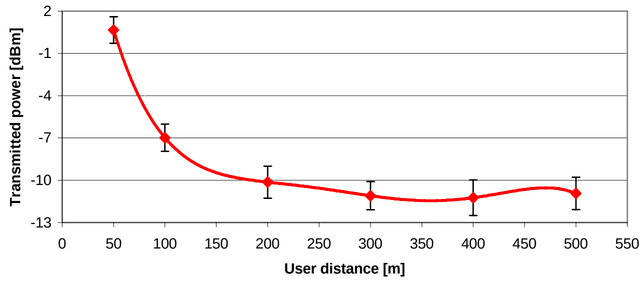

Fig. 1 Variation of the required MT transmission power, in the tunnel, for the default case.

The Carrier-to-Interference Ratio for the DL case is 13.6 dB, being around 10.2 dB for UL.

Concerning the tunnel dimensions, by increasing the width from 8 to 12 m causes an increase of about 3 dB in the BS transmission power, while the MT transmission power increases between 1 and 3 dB. Concerning the tunnel height, when a variation from 6 to 9 m is performed, the BS and MT required transmitted powers increase 4.4 dB, and 2 to 4 dB, respectively. This behaviour was expected, since the larger the tunnel dimensions the lower the waveguide effect is.

The variation of the number of users is also analysed. As expected, the power increases with the increase of the number of users, the difference between 5 and 35 users being around 28 dB. Regarding the MT transmission power, the increase among those cases is 22 dB.

An analysis for different BS 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. In what concerns the MT transmission power, a decrease from 4.4 to -1.9 dBm is observed between the same ranges.

The influence of the services performed by different users is interesting to analyse. In general, power increases 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. The MT transmission power exhibits a similar behaviour, it being between -10 and 12 dBm for all cases.

The influence of the BS antenna radiation pattern is important to analyse, since significant changes can be observed concerning coverage and capacity. The BS transmission power increases 4 dB comparing with the default case, when an omnidirectional antenna is considered. Regarding the MT transmission power, it is, in most of the cases, higher than that obtained in the default case, the difference 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 is observed in the BS transmission power. In what concerns the MT transmitted power, an increase between 11 and 13 dB is observed.

B. Bridge Case

Similar to the tunnel case, the default scenario for the bridge is also analysed, as well as some parameters variation.

The DL transmitted power exhibits an almost constant behaviour with the MT distance, which is expected. The values obtained for this parameter are around 31.1 dBm, thus, below the allowed maximum.

In what concerns the MT transmission power, Fig. 2 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 power from about -13 to 19.4 dBm, thus, still being below the allowed maximum.

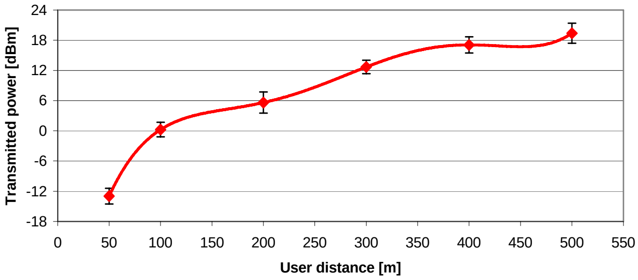

Fig. 2 Variation of the MT transmitted power, for the default scenario.

Regarding the number of users, the BS transmission power varies from 10 to 50 dBm, the lower being obtained for 5 users and the higher, above the maximum, for 35. Regarding the MT transmission power, the variation between 5 and 35 users is of 20 dB. For 25 and 35 users, power is above 21 dBm for some distances.

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

Regarding the MT transmission power, a decrease of about 11 dB is observed between 100 and 500 m.

The influence of the data rates is also studied in the bridge. The BS transmission power varies from 6 to 48 dBm. The limitations in capacity 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.

It is also important to analyse the variation in the results when other values for the *K* parameter from the Rice Distribution (ratio between the powers of the direct ray component and the random one) are considered. As expected, the transmission power decreases when the *K* increases. This decrease is in the order of 22 dB, between the extreme cases considered. In what concerns the MT transmission power, a similar increase is observed.

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. Regarding the MT transmission power, the same situation is observed.

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 main parameters and considerations taken are presented in [7].

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. 3.

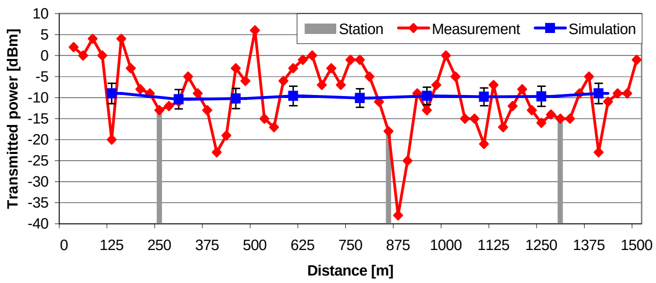

Fig. 3 Power transmitted by the MT between *Intendente* and *Alameda*.

The general average 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 received power obtained in the measurements and in the simulations, for the track considered, is presented in Fig. 4. The differences between both cases are caused by the assumptions taken in this study. In this case, the average difference between measurements and simulations is about 10.7 dB, the standard deviation being 7 dB.

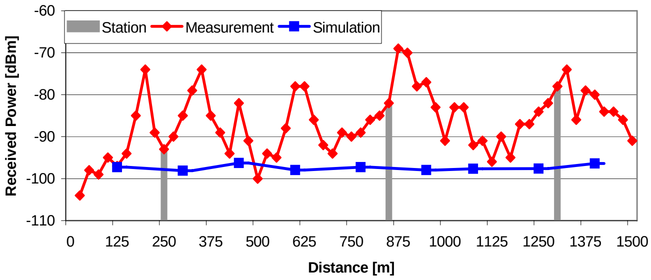

Fig. 4 Power received by the MT between *Intendente* and *Alameda*.

2) 25 de Abril Bridge

Regarding the measurements performed in the *25 de Abril* Bridge, the main results are presented in what follows. A detailed analysis is done in [7].

Concerning the MT transmission power, Fig. 5, it is possible to observe a very good agreement between measurements and simulations, the average difference being around 4 dB, the standard deviation 2.9 dB.

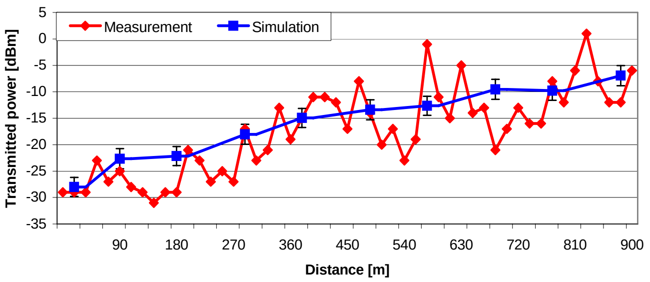

Fig. 5 MT transmitted power in the *25 de Abril* Bridge.

In what concerns the MT received power, the results for both cases are presented in Fig. 6. In this case, the average difference is 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.

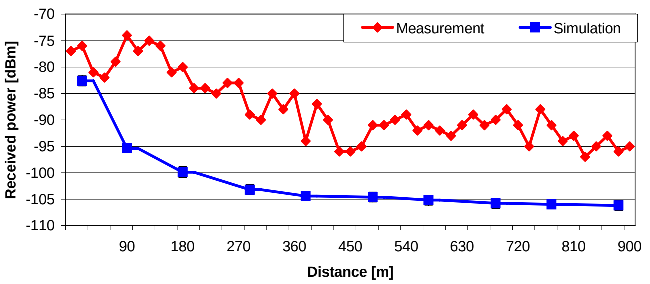

Fig. 6 Power received by the MT in the *25 de Abril* Bridge.

IV. CONCLUSIONS

The main objectives of this work were to study propagation, coverage, capacity and interference in tunnels and bridges, in UMTS. These goals were achieved through the development and implementation of models into a simulator.

Concerning the tunnel, it is observed that path loss is lower in comparison with other environments due to the waveguide phenomenon, confirming the theoretical expectations. Both BS and MT transmission powers are, for the default case, below the allowed maximum.

Some important results concerning coverage and capacity have been obtained, namely varying and studying the tunnel dimensions, the number of users and the BS range, among others. The variation of the BS antenna radiation pattern is also analysed. A directive antenna is more efficient than an omnidirectional antenna, in tunnels, since the required power is lower, thus, increasing coverage and capacity.

Concerning the bridge, for the default scenario, power in DL is 31 dBm, being between -13 and 19.4 dBm in UL. In this case, it is observed that more coverage and capacity problems are expected than in tunnels, since powers are above the allowed maximum in many cases.

Regarding the number of users, it is concluded that, with more than 15 users, coverage problems may exist, since powers are close to the allowed maximum.

The measurements performed in both the Lisbon Underground and the *25 de Abril* Bridge show that, in general, a good agreement is obtained with the results predicted by the model.

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