CELLULAR COVERAGE IN UNDERGROUND TRANSPORT SYSTEMS: A CASE STUDY – THE RIO DE JANEIRO METROPOLITAN

Marcio Rodrigues* **Bruno Maia***
Luiz Silva Mello** **Marlene Pontes*** ****

* WiNGS Telecom
** CETUC-PUC/Rio

INTRODUCTION

This paper presents a case study of cellular coverage in an underground transport system, the Rio de Janeiro Metropolitan. The project was developed at WiNGS Telecom and implemented by a pool of companies for Algar Telecomunicações Leste (ATL), the B-band operator in Rio de Janeiro, Brazil. The project characteristics, assumptions made and chosen solutions are described, as well as the propagation models, measurements and link budget examples.

THE RIO DE JANEIRO METROPOLITAN

The Rio de Janeiro Metropolitan is formed by 31 stations in two lines. Line 1 - shown in red in the figure 1 - has 16 stations and is entirely underground, with no coverage provided by outdoor Radio Base Stations (RBS). The main objective of the project was to provide coverage for this line, including its stations, platforms and the interior of trains running along tunnels. Line 2, shown in green in the figure, runs mostly on the surface, with coverage provided by the existing network, and was not subject of the project, except for its first hop, between the stations of Estácio and São Cristóvão.

Fig. 1 – Rio de Janeiro Metropolitan plan

The stations to be covered have three basic elements: the access at street level normally covered by outdoor base stations, the *mezzanine* (Figure 1) and the platforms (Figure 2). The *mezzanines* include a great hall with ticket boots and *kiosks*. Structurally, the obstacles to propagation are pillars and the *kiosks*. Fourteen stations have underground *mezzanines*. In the other two, *mezzanines* are at street level and coverage to then (the *mezzanines*) are provided by external RBS.

Figure 2 - Mezzanino – Uruguaiana Station

In all 16 stations to be covered, the platforms are underground. The platforms are large areas with central pillars separating two railroads (North-South and South-North).

Figure 3 - Platform – Cinelândia Station

Sixteen tunnels are to be covered: 15 in the Line 1 and one more connecting Line 1 to Line 2. In each tunnel there are two ways were the trains run simultaneously. The objective of the tunnel project is to provide coverage for users inside the trains when riding through tunnels.

PROPAGATION CONDITIONS

The indoor propagation depends on several different mechanisms including line-of-sight, multiple reflections, transmission through the floor and walls, scattering and diffraction. Unlike outdoor propagation, where one or two of these mechanisms may be dominant, here it is the combination of all effects that provides the propagation loss. The materials of the floor and walls also have great influence in the propagation loss. The ambient is difficult to describe, with many different materials and obstructions, limiting the accuracy of ray tracing techniques (a pretty accurate description of the ambient would be required for these techniques to be effective). Theoretical models for propagation in tunnels are available in the literature [1-4] but usually consider single straight or curved portions of tunnels.

Inside empty portions of tunnels one can expect some degree of wave guidance, as the walls will provide strong reflections, eventually leading to signal above free space level. However, in the presence of a train, the cross section of the tunnel is almost entirely obstructed and the attenuation is high. In the particular case of the Rio de Janeiro Metropolitan, the propagation will take place in narrow gaps between the train and the tunnel walls, as illustrated in Figure 4. Considering this situation, the solution adopted was to dispose antennas along the tunnel walls at the level of the train windows. The alternative would be the use of open coaxial lines running along the tunnel walls. This alternative, however, would imply in higher cost and longer implementation time. To evaluate the propagation loss and define the number and position of the antennas, propagation measurements were performed, as described later.

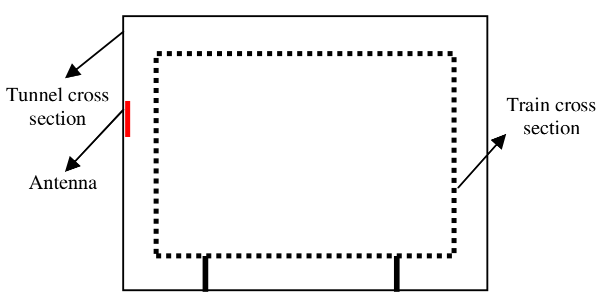

Fig. 4 – Tunnel Cross Section

SYSTEM TOPOLOGY

The development of the project for coverage of the Rio de Janeiro Metropolitan followed five steps:

- System topology definition;
- Initial design;
- Propagation tests in stations and tunnels;
- Final design;
- System optimization and measurements.

The system topology was defined based on traffic predictions provided by the system operator, ATL. The number of RBS and the stations were they should be installed were chosen based in traffic capacity to be offered. Three radio base stations (RBS) were planned, in the stations of Afonso Pena (AFP), Carioca (CRC) e Flamengo (FLA). The remaining stations are served by repeaters that, although providing adequate signal levels, do not increase the traffic capacity of the system. Figure 5 illustrates the final topology of the system. The connection between the radio base stations and the repeaters was provided by optical fibers.

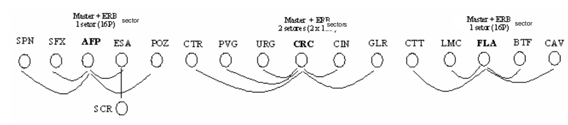

Fig. 5 – System topology

INITIAL DESIGN

The initial design for the stations was based on three main requirements:

- To provide appropriate coverage inside stations and steady or moving trains;
- Inside the stations, the best server should be always one of the sectors of the three radio base stations, either directly in the stations where they are installed or through repeaters for the other stations, avoiding coverage by other surface stations of the systems which have their own traffic load;
- Flawless handoff between stations *mezzanines* and outdoor locations should be provided.

The position of the antennas in stations was defined considering that the antenna input power level is highly dependent on the cable deployment, which is a critical point in the design due to limited possibilities resulting from both physical and esthetic constraints. In many cases it was necessary to include signal boosters in addition to the repeaters.

In the tunnels, the main factor to be taken into account when choosing the antennas positions is the loss of visibility along curved portions of the tunnel. It was observed that the propagation loss increase is prohibitive in these cases. To avoid this problem, additional antennas were placed in just after the points of visibility loss. In straight portions of the tunnels, the antennas were placed in regular intervals to provide a 30% theoretical overlap in coverage distance.

The design of antenna positions and the use of signal boosters were based on link budgets for the downlink and uplink calculated for each station. Figure 6 shows an example of the signal distribution design for a typical station.

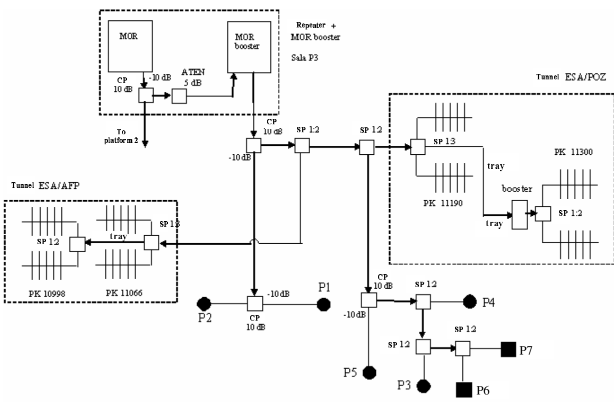

Fig. 6 – Power Distribution Diagram Sample

Downlink budget

$$EiRP_{down} = P_T - L_{splitters} - L_{cables} + G_{ant} + G_{booster} \quad (1)$$

$$RSL_{mob} = EiRP_{down} - L_{train} - L_{down} \quad (2)$$

$$RSL_{mob} = S_{mob} + M_{down} \quad (3)$$

$$L_{down} = EiRP_{down} - L_{train} - S_{mob} - M_{down} \quad (4)$$

where: $EiRP_{down}$ is the RBS effective radiated power;
P_T is the output power of the RBS or repeater;
$L_{splitters}$ are the splitters losses;
L_{cables} are the cables losses;
G_{ant} is the antenna gain;
$G_{booster}$ is the booster gain;
RSL_{min} is the minimum allowed signal level at the mobile terminal;
S_{mob} is the mobile terminal threshold;
M_{down} is the downlink fading margin;
L_{train} in the train penetration loss;
L_{down} is the maximum allowed propagation loss in the downlink.

Uplink budget

$$EiRP_{up} = P_{mob} \quad (5)$$

$$RSL_{min} = EiRP_{up} - L_{train} - L_{up} \quad (6)$$

$$RSL_{min} = S_{eff} - G_{ant} + M_{up} \quad (7)$$

$$L_{up} = EiRP_{up} - L_{train} - S_{eff} - M_{up} + G_{ant} \quad (8)$$

where: $EiRP_{up}$ is the mobile effective radiated power;
P_{mob} is the output power of the mobile station;
RSL_{min} is the minimum allowed signal level at the RBS;
S_{eff} is the effective threshold;
M_{up} is the uplink fading margin;
L_{up} is the maximum allowed propagation loss in the uplink.

The effective threshold is defined considering that the RBS receives the signal through an optical connection after it has been enhanced by a repeater and (eventually) a booster and attenuated by splitters and cables. It also takes into account additional noise from other antennas connected to the repeater.

$$S_{eff} = S_{RBS} - G_{rep} - G_{booster} + L_{optic} + L_{splitters} + L_{cables} + Deg \quad (9)$$

where: S_{RBS} is the base station threshold;
G_{rep} is the repeater gain;
$L_{optical}$ is the optical fiber loss;
Deg is the degradation due to additional antennas (degradation by noise increase).

PROPAGATION TESTS AND FINAL DESIGN

The initial design included a series of assumptions that required experimental evaluation before the final design could be completed. To allow this, propagation measurements were performed in all stations and several tunnels. As far as possible, it has been attempted to simulate actual operation conditions, performing some of these tests during rush hours.

A simple set-up was used to perform the measurements in stations, including a RF generator with output power of 3 dBm and an omni directional antenna with 2 dBi gain. This set was installed at every point indicated in the initial design. The received signal was then measured in several points in the *mezzanine*, platforms and inside trains using a portable terminal *TEMS Pocket* (Ericsson). Handoff conditions were also tested using a Nokia 6020i terminal operating in test mode.

One of the main results of the tests was the measurement of the penetration loss for trains. Average values of 6 dB and 12 dB were obtained for off and rush hours, respectively. The value of 20 dB, adopted in the initial project was maintained, to allow for extreme values and provide some additional margin.

The propagation measurements inside the tunnels were performed using YAGI antennas with 14 dBi gain. The portable terminal was used to measure the signal intensity along the tunnel. The results were used to adjust the method for predicting the propagation loss inside the tunnels. Sample results are shown in Figure 7.

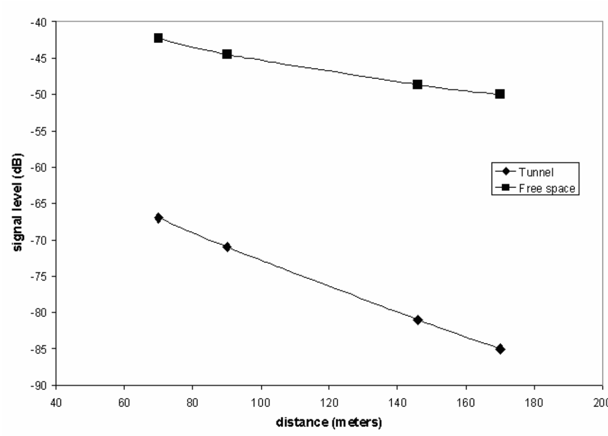

Fig. 7 – Signal strength curve for a portion of a tunnel

By using the propagation tests results as a feedback to the initial design, a final design for stations (mezzanines and platforms) and tunnels was accomplished.

SYSTEM OPTIMIZATION AND MEASUREMENTS

The next step, that takes place with the system already under commercial operation, is the adjustment of system parameters.

To verify how the system has reacts to each parameter adjustment, a series of propagation tests were made (in tunnels). The main measurements were:

- Received power at the mobile terminal;
- BER at mobile receiver;
- Mobile transmitted power;
- Handoff occurrences;
- Call drops.

A typical measurement result is shown in Figure 8. Signal levels are indicated by colors green (-80 to -70 dBm) and yellow (-90 to -70 dBm). The radius of each plotted signal is proportional to the bit error rate (BER) at the specific point, the smaller radius corresponding to lower BER.

The main purpose of test campaigns is to provide feedback for system parameters adjustments, but the results are also useful to allow better understanding propagation characteristics in tunnels. The measured data can be processed to provide the signal variations inside the train as it moves along the tunnel. By identifying peaks in the signal and relating these peaks to antenna positions, the propagation in portions of the tunnel confined between two consecutive antennas can be analyzed. The time scale can be – with small degree of error – converted into a distance scale using the train speed.

One example of signal variation along the tunnel is shown in figure 9. A section between two antennas, indicated in figure 10, was selected and a regression line was adjusted to each portion of the curve. In this particular case, the distance attenuation factor is 22 dB/decade.

CONCLUSIONS

This paper describes the cellular coverage system design and implementation for the Rio de Janeiro Metropolitan underground transport system. The threshold degradation due to the use of several antennas to provide coverage in tunnels and platforms is analyzed and complete link budget equations obtained.

In the optimization phase of the project, now underway, measurements are being performed that will provide useful experimental data for modeling signal propagation in underground tunnels.

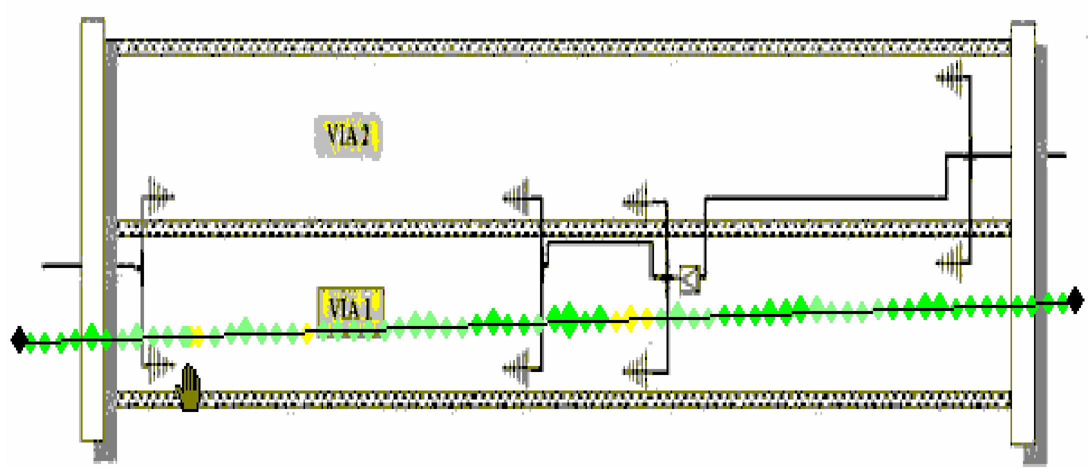

Fig. 8 – In-train measurement sample

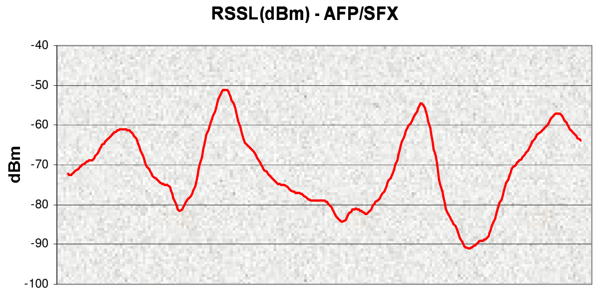

Figure 9 – Power received along a tunnel

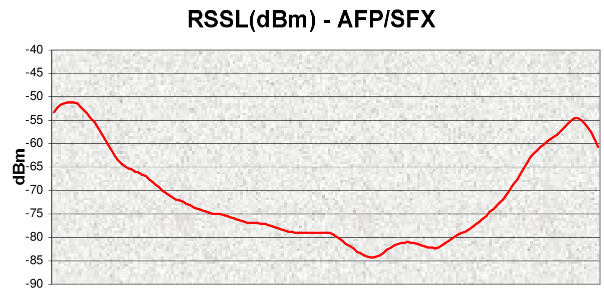

Fig. 10 – Power received between two antennas

REFERENCES

[1] Popov, A.V. and Ning Yan Zhu, *Modeling radio wave propagation in tunnels with a vectorial parabolic equation*, IEEE Transactions on Antennas and Propagation, Vol. 48, Issue 9 , Sept. 2000, pages 1403 -1412.

[2] El-Sallabi, H.M. and Tervonen, J., *Characterization of radio wave propagation in tunnels for microcellular communications,* 2000 IEEE-APS Conference on Antennas and Propagation for Wireless Communications, pages 91 - 94.

[3] Lienard, M.; Betrencourt, S. and Degauque, P., *Theoretical and experimental approach of the propagation at 2.5 GHz and 10 GHz in straight and curved tunnels,* IEEE VTS 50th Vehicular Technology Conference, 1999 pages 2268 -2271.

[4] Zhang, Y.P. and Hwang, Y., *Theory of the radio-wave propagation in railway tunnels*, IEEE Transactions on Vehicular Technology, Vol. 47, 3, Aug. 1998, pages 1027 - 1036.