Indoor penetration of outdoor urban UMTS coverage: an experimental model

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Abstract—The development of the new third generation cellular system, the UMTS, makes an extensive use of microcells and picocells other than macrocells: picocells are especially used to offer indoor radio coverage. Usually, indoor coverage design is modeled by disregarding the outdoor signal and by analyzing only micro and picocells placed indoor. This paper investigates the importance of the signal penetrating through windows and the measurements performed highlight how to decouple outdoor and indoor effects by modeling windows as equivalent radiating antennas. This solution can be used as a precious support to indoor cellular design.

I. INTRODUCTION

Nowadays, almost every person living in a city owes a mobile phone: this is probably the most important and common communication medium ever made available to mankind by technology. In the last two years, users are moving from the old second generation (2G) systems (e.g., the GSM system in Europe) to the new, multimedia oriented, third generation mobile system: the UMTS. This new standard has been developed to overcome the constraints characterizing the old systems: limited bitrate and difficulties to manage large numbers of users [1].

UMTS system has been designed to handle a great number of users and to provide variable bitrates up to 2 Mb/s: this allows to develop new multimedia applications such as video calls, video streaming or web browsing with high quality [1], [2]. All these improvements are possible thanks to the CDMA (Code Division Multiple Access) approach chosen to access the radio channel: CDMA, in fact, allows to handle many users without increasing complexity or interference, and easily manages simultaneous multimedia streams at different rates [1].

Perhaps, one of the most important aspects of cellular networks design is the access network and in particular the cellular coverage design. Coverage is designed, in 2G systems, mainly by using macrocells and by overlaying microcells where such coverage is not sufficient. The UMTS system, instead, extensively uses microcells because short radius cells allows to better implement power control mechanisms, [3], and, by reducing the interference, to achieve higher communication rates [4]–[6].

The study of propagation, especially in urban environments, is very difficult because it is hard to predict signals behaviour [7]. Macrocells propagation models exist and well predict signal behaviour even if they are almost empirical; raytracing instead is the most used approach when microcells are studied.

Considering both the approaches, a critical issue in cellular coverage design is the study of the indoor coverage. Some studies solve this problem by assuming a loss coefficient for signals penetrating into buildings (e.g., [8] where the authors analyzed propagation at 1.8 GHz and [9] where validation is performed at 900 MHz). In ray-tracing simulators, indoor penetration can be taken into account in a more precise way by modeling building walls as described in [10].

More practical solutions, instead, study indoor coverage by designing new picocellular coverage without taking into account outdoor cells.

This paper presents a new solution to this problem by analyzing signals radiated from outdoor UMTS base stations that penetrate into building through windows or wall slots [11]. Windows (under some hypothesis) are modeled as rectangular slots in a perfect conducting plane by considering the usually present metallic frame around them. Modeling this slot as an equivalent antenna allows to study separately outdoor and indoor propagation [12].

The paper is organized as follow: in Sec. II the model is described, in Sec. III the measurements performed are described and the results are analyzed. Finally, in Sec. IV conclusions are drawn.

II. WINDOW AS AN ANTENNA

In this section the model of a window as an aperture in a conductive plane will be described and analyzed.

The model is based on the diffraction Fresnel formula built upon the Huygens principle: it states that the wavefront of a propagating wave of light at any instant conforms to the envelope of spherical wavelets emanating from every point on the wavefront at the prior instant.

Considering a rectangular aperture with dimensions a and b on the xy plane, Fresnel diffraction calculates the diffraction field caused by the interaction of the incoming wave with the aperture. For our purpose, the most relevant aspects are how power is distributed in the space behind the aperture and how power decreases while moving away from the window.

The power decrease with distance from the aperture is described by the Poynting vector along z axis as shown in (1).
\[ S(z) = \frac{S_0}{4} \left[ 3 \left( \frac{2}{\lambda z} (x + \frac{a}{2}) \right) - 3 \left( \frac{2}{\lambda z} (x - \frac{a}{2}) \right) \right]^2 \cdot \left[ 3 \left( \frac{2}{\lambda z} (y + \frac{b}{2}) \right) - 3 \left( \frac{2}{\lambda z} (y - \frac{b}{2}) \right) \right]^2. \]

\[ S_0 = \frac{1}{2\eta} \cdot (E_{0x}^2 + E_{0y}^2) \]

where \( \eta \) is the characteristic impedance.

To model the equivalent antenna we used a very simple approach: we hypothesized the window as an aperture antenna having the effective aperture equal to the area of the window; then we powered the equivalent antenna so as to get the same Equivalent Isotropically Radiated Power (EIRP) as the window. To do that, the gain of the window, \( G_{\text{win}} \), has been evaluated under the same hypothesis and, furthermore, the efficiency has been set equal to one for simplicity.

\[ G_{\text{win}} = A_{\text{win}} \cdot \frac{4\pi}{\lambda^2} \]

Then, matching the EIRP of the window, \( \text{EIRP}_{\text{win}} \), and that of the equivalent antenna, \( \text{EIRP}_{\text{eq ant}} \),

\[ \text{EIRP}_{\text{win}} = \text{EIRP}_{\text{eq ant}} \]

the power \( P_{\text{eq ant}} \) to be used to transmit with the equivalent antenna can be calculated

\[ P_{\text{eq ant}} = P_{\text{irr}} \cdot G_{\text{win}} / \text{EIRP}_{\text{eq ant}} \]

where \( P_{\text{irr}} \) is the power reradiated by the window.

The model proposed is very simple but it matches quite well the recorded data as can be seen in the next Sec. III where (1) has been evaluated for \( x \) and \( y \) equal to zero (see Fig. 1).

During this study only the EIRP has been exploited to characterize the equivalent antenna, but other characteristics have to be analyzed in order to have a good model for this kind of propagation. Two of the most important characteristics are the width of the beam of the window and the angle of incidence of the outdoor electromagnetic field on the window.

The former mainly affects indoor signal behaviour: reflections on corridor’s walls, cell and floor as well as on walls in near rooms are significantly affected by the main beam width so this subject will be investigated with further studies. Probably some of the mismatches in the figures shown in Sec. III are due to the differences between the two beams.

The incidence of the outdoor field, instead, affects both the power that the window irradiates into the building and, probably, the shape of the beam itself: other tests will be carried out to investigate this aspect.

The last point to be remarked is that the measurements have been carried out by using always the same antenna: to better analyze the behaviour near the window, that is in the so called near field region, aperture antennas having the same shape and dimensions of the window under exam will be used during next measurements.

## III. MEASUREMENTS AND CONSIDERATIONS

Tests carried out during this work have been divided in two parts. First we considered large windows which allow to better analyze fast oscillations near the aperture. If too small apertures are considered, these oscillations happen in a very short range and our measurement devices have physical size that prevents from reliable appreciation of such fast signal fluctuations. Second, we considered smaller windows to analyze signals far away from the aperture thus neglecting short range fast fluctuations. In this second part, we measured signals radiated from the aperture and also from an equivalent antenna placed in correspondence to its location and the results of the comparison are shown.

Locations chosen for these experiments are corridors, except one location (see Fig. 2), because their almost regular structure guarantees a more regular propagation.

Figure 1 shows the two setups used during the experiments. In the first sub-figure the setup with the transmitting antenna placed outside the building is shown: the signal radiated by this antenna penetrates into the building through the window, drawn in the middle, and it is received by the receiving antenna installed on a trolley. Signal is recorded starting close to the window and by moving away the trolley along the corridor.

The second sub-figure of Fig. 1 shows the setup used to validate the hypothesis that windows can be modeled as equivalent antennas. Now, the outdoor antenna is switched off and a real equivalent antenna is put in the place of the window with the signal radiated with as much power as necessary to get the same EIRP as in the previous case.

The settings and the equipment used during the measurement campaign have been:

- Operating frequency: 2.1626 GHz;
- Polarization: vertical;
- Recorded data: samples of the Received Signal Code Power (RSCP), that is the received power on one code measured on the pilot bits of the Primary Common Pilot Channel (P-CPICH) after despreading [1];
- Transmitter: Wideband CDMA SeeGull transmitter transmitting P-CPICH;
- Transmitting antenna: Kathrein panel antenna, 7 dBi, 90°;
- Receiver: SeeGull LX UMTS WCDMA receiver, [13], equipped with an omnidirectional antenna.
Data recorded during the measurements have been filtered to remove fast fading components because they are not relevant for the study presented in this paper.

A. Large window

In this section the measurements recorded with large windows are shown: such large apertures allow to better appreciate the fast fluctuations that take place near the aperture. Test-beds and measurements results are described in the next figures.

Figures 2 and 3 show the comparison between the received signal and the aperture model. As can be seen, due to the large width of the window considered, the oscillations take place in several meters (except the very fast ones near the window) and so they can be easily analyzed in the recorded signal.

In Fig. 2, errors between the signal and the model increase much more than in Fig. 3, in particular after 5 meters from the window: this behaviour can be explained because, in the first scenario, measurements were collected in a room and not in a corridor. Moreover, since there are several other windows in this environment, when the distance from the window increases, interference with signals penetrating through the other windows increases as well as errors with the model which takes into account only the effect of one window.

Anyway it can be seen that the recorded signal well fits the model response in the first part near the window: despite fast fluctuations of the signal, the global trend of the received signal is well predicted by the studied model.

B. Small window

This section shows, on the contrary, the measurements performed with small size windows: this time only the asymptotic behaviour of the signal, that is far away from the window, is analyzed. Furthermore, during these measurements, we also compared the signal propagating through the aperture and the signal radiated by an equivalent antenna. Test-beds and measurements results are described in the next figures: in the caption of each figure the values of the parameters shown in Fig. 1 are listed.

Figures 4 and 5 show the results of the experiment carried out along two corridors with a very regular structure (walls and ceil are very smooth), nevertheless in the second scenario (i.e., location D), at about 13 meters from the window, there is an opening in the corridor which influences the signal beyond it.

The two corridors end with back doors with very large windows: to get a smaller window we used a plywood board in which we cut an aperture having the right dimensions. All this structure was wrapped with tinfoil to simulate windows’ frames.

Results of the experiments are shown in the figures with thick solid line and dotted line. It is clear that all recorded signals’ trends match with the model when considered after few meters from the window. Furthermore, if the signal radiated by the aperture is compared with that radiated by the equivalent antenna, it is clear that the window really acts as an aperture antenna: the two signals have the same shape and exhibit exactly the same distinctive behaviour.

Figure 6 shows the result of the measurements performed along a corridor by considering a small window being in a fire
This window has not the same size of the aperture used during previous experiments but we used the same antenna as the equivalent antenna: differences between model and data are not so high owing to the little differences between the dimensions of the windows analyzed. Although also this experiment shows that signal radiated by the equivalent antenna matches with that radiated by the window, at 10 metres the two signals slightly differ: this fact is probably due to the not matching radiation diagrams and to the window’s frame more complex shape. Notwithstanding this, global signals’ behaviours and model agree. These results confirm the hypothesis that power is radiated by windows as they would be aperture antennas: because characteristic behaviours are due to interference with reflected signals and because these distinctive trends happen at the same places, it means that the window acts as the equivalent antenna used, with a similar radiation diagram too.

Comparing results shown in Sec. III-A and III-B it can be asserted the proposed model is well suitable to predict signal penetrating through large windows. On the contrary, small windows effect can be more easily modeled considering a FSL model.

Table I shows the errors statistics between recorded data through window and the proposed model while Table II lists the error statistics between data collected from signals propagating through the windows and from signals radiated by the equivalent antenna.

<table>
<thead>
<tr>
<th>Location</th>
<th>Mean error (dBm)</th>
<th>Standard deviation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.1243</td>
<td>3.7234</td>
</tr>
<tr>
<td>B</td>
<td>2.6608</td>
<td>1.9137</td>
</tr>
<tr>
<td>C</td>
<td>-2.2498</td>
<td>3.6137</td>
</tr>
<tr>
<td>D</td>
<td>2.0747</td>
<td>4.9546</td>
</tr>
<tr>
<td>E</td>
<td>-2.2549</td>
<td>6.5947</td>
</tr>
</tbody>
</table>

**Table II**

<table>
<thead>
<tr>
<th>Location</th>
<th>Mean error (dBm)</th>
<th>Standard deviation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>-0.3535</td>
<td>6.2559</td>
</tr>
<tr>
<td>D</td>
<td>5.1111</td>
<td>5.3256</td>
</tr>
<tr>
<td>E</td>
<td>-2.7778</td>
<td>5.5756</td>
</tr>
</tbody>
</table>

**IV. Conclusion**

In this paper a study about propagation of outdoor UMTS signals in indoor environments has been carried out. An equivalent model for the propagation through windows is proposed. Indoor cellular coverage is commonly tackled by using microcells or picocells disregarding the already existent outdoor coverage. To improve this approach, signals coming from apertures in the buildings, such as windows, might be
taken into account: outdoor coverage can be exploited also in indoor environments. The study of signals reradiated from windows shows that these apertures can be well modeled by equivalent antennas: aperture diffraction model shows a good match with recorded signals. A set of measurements along corridors ending with windows have been carried out and signals radiated by the equivalent antennas have been recorded as well and compared with the previous ones. This is only a preliminary study and further in-depth examination will be accomplished.

Despite its simplicity, the model is quite robust and shows appreciable results as the figures reported show.

REFERENCES


