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3D Indoor Radio Coverage for 5G Planning: a Framework of Combining BIM with Ray-tracing

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***Abstract*—This paper presents a framework to predict indoor radio wave coverage in buildings. Such method includes the capability to import BIM (Building Information Modelling) files that contain structured physical geometry and dimension data, including the material types that are of uttermost importance in evaluating their dielectric properties. Appropriated extraction of physical and dielectric attributes of the building elements was used as input to a 3D radio wave propagation ray-tracing developed in MatLab that allows the prediction of the received radio signal level at any location within the computational volume. Results are presented for line-of-sight contributions and first and second order reflections. Despite the generic nature of the proposed framework, prediction results are presented at 3.6 GHz, envisaging emerging 5G indoor radio coverage.**

Keywords—radiowave, 5G, indoor coverage, ray-tracing, BIM

I. Introduction

Building Information Modelling (BIM) is a key technology and methodology to improve productivity and integration across various disciplines throughout the Architecture, Engineering and Construction and Operation (AECO) value chain [1]. BIM aims to share construction information that is generated and maintained throughout a building's life cycle. This is a computable representation of all characteristics of a building [2], but it is not same as computer-aided design (CAD) [3]. Therefore, developing an effective solution that combines real-world facilities with a BIM model is significant work in the construction operations and facility management stage [4], [5]. Although many valuable information has been added to such databases in the recent years, detailed information about the radio wave propagation characteristics of buildings and building materials is not yet available. With the deployment of an ever-increasing number of radio-based services, such as 5G, this information is expected to be extremely important in the future, both for appropriate indoor radio planning and for the assessment of human exposure to electromagnetic radiation.

To overcome the absence of information, a framework capable of reading building geometry and construction elements data from IFC files is proposed. Additionally, the proposed framework integrates a ray tracing simulation tool able to predict the radio coverage in indoor environments. The ray tracing tool takes into consideration not only reflection from walls, but also the multilayer dielectric nature of typical building walls. These include their electromagnetic dielectric proprieties for a wide-range of frequencies. This framework will be important in the design of new construction of buildings supporting the definition of the constructive solutions, bringing together architecture, traditional construction and digital tools. It will be possible to design buildings with a controlled frequency response, such as, for example, electromagnetic transparency in emergency radio frequencies and shielding in other undesirable frequencies.

The paper is organised in 6 sections. Following this section, description of the framework is presented, with the aid of a block diagram. After that, the building prototype considered to validate the proposed framework is presented in detail. This is followed by a description of the sub-modules: IFC data conversion, Multidielectric Simulator and Ray Tracing. At the end, the results are presented and conclusions are drawn.

II. Description of the Framework

The process of designing a building is complex and requires the involvement of various professionals from different fields (architects, civil engineers and other engineers). The coordination between these fields and the professionals is mandatory and, consequently, the use of BIM workflow to interchange information throughout the design process, is highly recommended [1]. The proposed framework, logically depicted in Figure 1, takes benefit of the BIM workflow files as input data for four main modules:

- Main process;
- IFC data conversion;
- Multidielectric Simulator;
- Ray Tracing.

The main process is responsible for coordinating the remaining modules. The IFC data conversion module, reads IFC file providing the essential information about the building geometry and properties of the constructive, in particular walls and slabs. The multidielectric plug-in is responsible for the calculation of the relative transfer function of each material in the computational volume as a function of the incidence angle. Finally, the ray tracing module gathers the information about the

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transmitted signal and computes the various radio signal paths to yield the received signal strength (RSSI) within the entire simulation space. These modules are explained in more detail in the next sections.

III. SIMULATION SCENARIO

A prototype building was defined and used for the simulation scenario presented in this paper and was modelled using AutoDesk Revit. This allows to define the building components, namely the structural and non-structural building components. Depending on the level of detail (LOD), it includes the 3D geometry of the building model and different levels of refinement, related with the modelling of the building elements components and it can go as far as details of size, shape, location, quantity, and orientation, and non-geometric information that is attached to

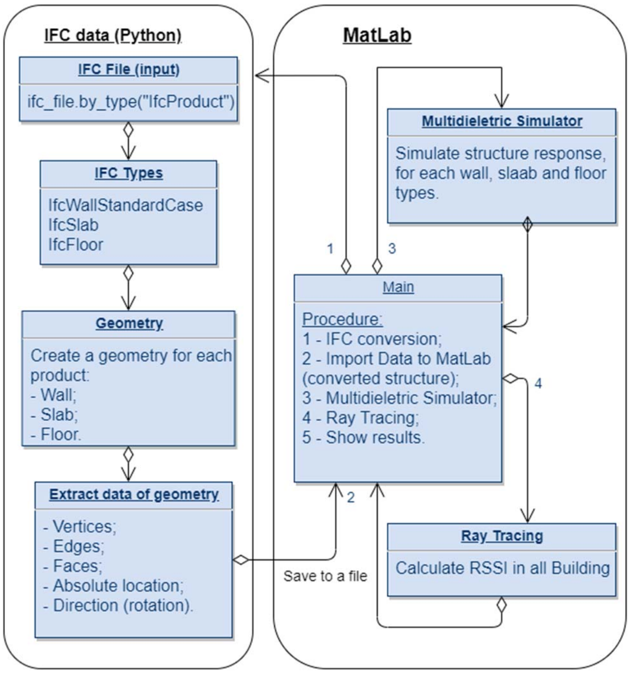

Figure 1- Block diagram of the framework implementation.

the properties of the modelled element. To this extent, the user may also add specific details of each element or object in the database, e.g. technical specifications from manufacturer datasheets, price, manufacturing time, etc., and non-geometric information is associated to the modelled element in its properties database field. Revit and all the other BIM softwares provide several formats for exporting data, including the IFC (industry Foundation Classes) format, which has been adopted in this study. The IFC is a standard format that allows the data exchange between different software and based on this, the proposed framework can work with Revit or with any other BIM modelling software.

The building prototype considered to validate the proposed framework, is presented in Figure 2 (sectional view). The building is divided in four spaces, labelled as A, B, C and D. It contains four exterior walls, one interior wall per floor,

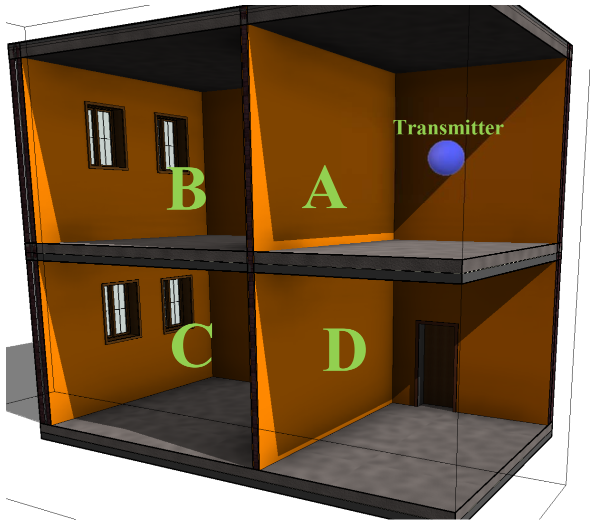

Figure 2 - Building sectional view.

two floors, one flat roof, five windows and one door, as shown in Figure 2.

The exterior walls are multilayer type that have been chosen to be representative of the main building techniques employed in the Portuguese building context. The main characteristics of the exterior walls are:

- Interior and exterior plaster (20mm thick);
- Two leaf's of clay brick, where exterior leaf with150mm and interior leaf with 110 mm thickness;
- One internal air space (30 mm);
- one layer of rigid insulation (40 mm).

The interior wall was designed from a single leaf wall with clay bricks (110mm) and two layers of plastering, one in each face (20mm) of the wall.

The floor consists of a superficial layer of reinforced concrete, cast in sit (200 mm), an intermediate layer of sand (12mm) and an additional layer of concrete (150 mm).

The roof was designed based on the following four layers:

- Asphalt, Bitumen (20mm);
- Rigid Insulation (50mm);
- Reinforced concrete layer (50mm);
- Reinforced concrete layer, Cast In Situ (175mm).

The model used for the simulation of the radio wave propagation, currently does not consider windows nor doors and consequently, these were ignored in the simulation geometry and, thus, have been replaced by empty spaces (air) blocks. It should be noted that this is just an illustrative building, where it is possible to verify several radio propagation phenomena.

The blue sphere depicted in 'A' room represents the position of the transmitter. Note that only one transmitter is used, and it is two meters above on the second floor, which means that it is equidistant from the ceiling. The letters in Figure 2 identify the building's rooms.

In Figure 3, only the door and windows are visible, as well as three windows and one door on Level 1 and two windows on Level 2. The transmitter is on Level 2, in the room opposite to the windows.

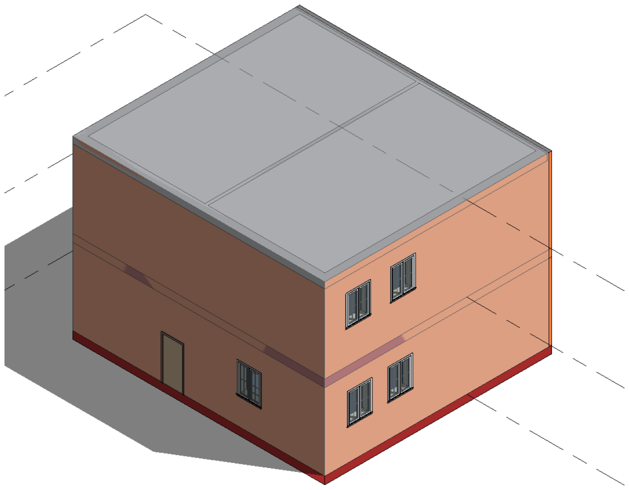

Figure 3 - Exterior building view.

IV. IFC DATA CONVERSION MODULE

This module enables to import BIM structures from IFC files, using IfcOpenShell software, which has been written in Python language. IfcOpenShell is an open source software library that allows the manipulation of BIM information in IFC format. Using these routines, it is possible to extract information from a building or add new components to an existing project (walls, doors, windows…).

For the study presented in this paper, it is imperative to know the geometry of each element forming the building, by knowing *a priori* the absolute position of each vertex, edge and face of such components. These characteristics are extracted directly from the IFC file and are stored in a CSV file, which is then imported into MatLab for post-processing. Although BIM is capable of providing a plethora of site-specifics information, only information about walls, slabs (layers) and floor, is relevant for the time being.

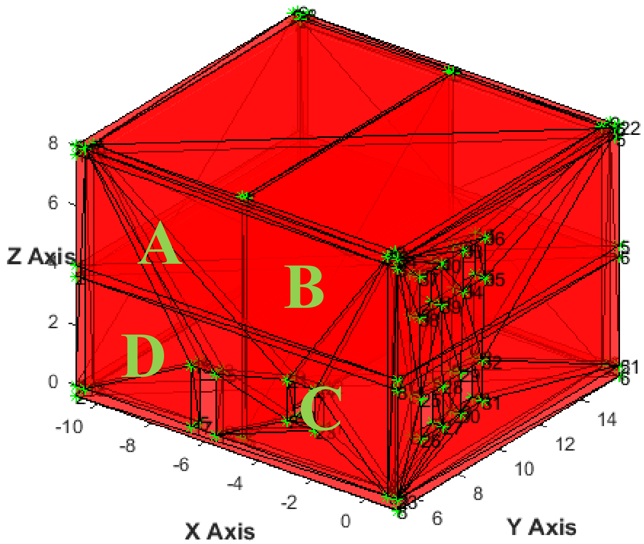

Figure 4 - Imported structure (Matlab).

The final structure imported into MatLab is presented in Figure 4. As shown, the walls are assembled by joining several triangles in a triangulation approach. In Figure 4, it is already possible to check the dimensions of the building, by using the relevant reference axis.

V. MULTIDIELECTRIC SIMULATOR

The walls used in the construction of buildings rarely have only one layer, so it is important to calculate the component reflected and transmitted (refracted) by the different walls of a building. A multilayer EM simulation tool was developed in MatLab [6], which allows to explore different layer sets and determine the frequency response per unit incident angle. This simulation tool allows to compute up to 10 layers, which may be defined by complex dielectric properties (*user_defined* thickness) or S-parameters.

This tool is mainly based in the transfer matrix theory described in [7] to simulate walls with multiple cascading layers of homogeneous or heterogeneous materials. Fig. 1 presents a diagram of any wall with multiple homogeneous cascaded slabs (layers), more specifically i slabs, $i + 1$ layer transitions and $i + 2$ media, where are included the semi-infinite media η_a and η_b.

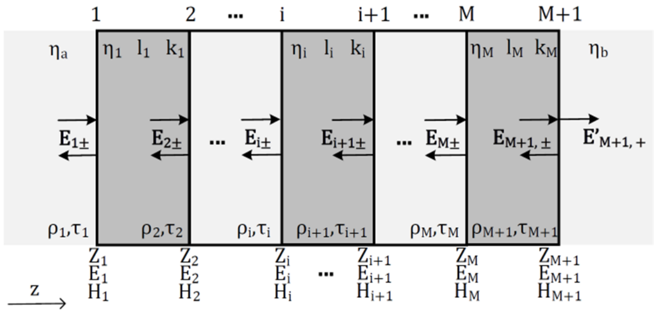

Figure 5 - Multilayer slab structure [6].

VI. RAY TRACING

Finally, this sub-module of the main process is a 3D Ray Tracing [8] algorithm for simulate the radio propagation in indoor environments and its surrounding area. It presents the end result of main component, first reflection and secondary reflection of an electromagnetic signal, based on reflecting image method and Snell's law of reflection and refraction.

In this simulation tool, each wall, slab, or floor is characterised by a set of several surfaces defined by three points (triangulation), so these components are defined in 3D, but with no thickness. That is to say only the face of the wall is taken into account. This can be observed in Fig. 6.

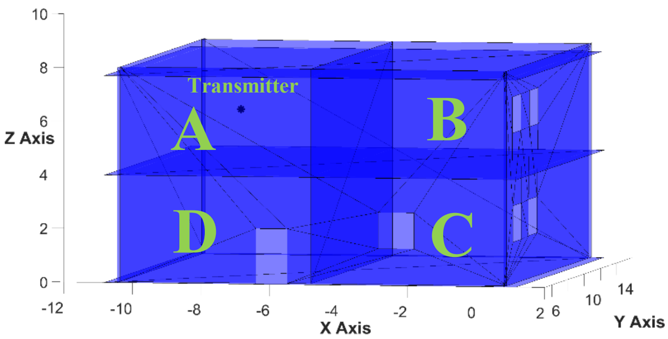

Figure 6 - Extracted faces (closest to the transmitter).

VII. RESULTS

Simulation results are presented in terms of indoor radio coverage, in Fig. 6. For this, isotropic antenna has been considered and 0 dBm of effective isotropic radiated power (EIRP) was set. Direct signal and up to second order reflections have been considered for the received signal level calculation across the computation volume, at 3.6 GHz. The transmitter is represented by a black dot and is placed in the second floor, at 6 meter above the ground level, position coordinates.

Results presented in Figs. 7 to 10, clearly demonstrate the capability of the proposed framework to provide radio coverage maps directly from BIM databases, which represents a leap advance in propagation tools for realistic indoor coverage prediction. This is of uttermost importance at present, in which the specifics of the indoor building will enable not only better design of indoor radio networks using real features of the buildings, but also provide engineers with a tool that readily provide physical insights into the radio transparency of buildings at early design stages, paving the way to more radio efficient buildings in the near future.

The actual validation of the ray-tracing algorithm is out of the scope of this paper.

VIII. CONCLUSIONS.

This paper fills in a gap in the literature by building upon existing BIM databases to generate the appropriate indoor scenarios for radio wave propagation. It is highly recommended that in the future, BIM databases are improved to contain dielectric properties of each constituent of the building materials, so that readily plug-in tools as the one presented in this paper, can import geometries from existing BIM models to enable prompt results for radio designers on the radio transparency efficiency of the building and radio coverage maps for quick deployment of e.g. 5G femtocells. Indeed, radio engineers should further populate the BIM databases with the dielectric properties of other existing and new materials for an all-encompassing framework. Also, convergence with building penetration losses proposed by ITU would be a must have feature in this framework whenever the specifics of the materials (including the electromagnetic properties) are not readily available.

Future work will address the improvement of the ray-tracing algorithm, so that higher order reflections and diffraction around the edges and wedges can be accounted for. Both angle of arrival and complex channel impulse response, appropriately convolved with any complex radiation pattern of the antenna will prove to be a valuable tool to assist radio engineers in the effective planning and deployment of emerging 5G indoor networks.

ACKNOWLEDGMENTS

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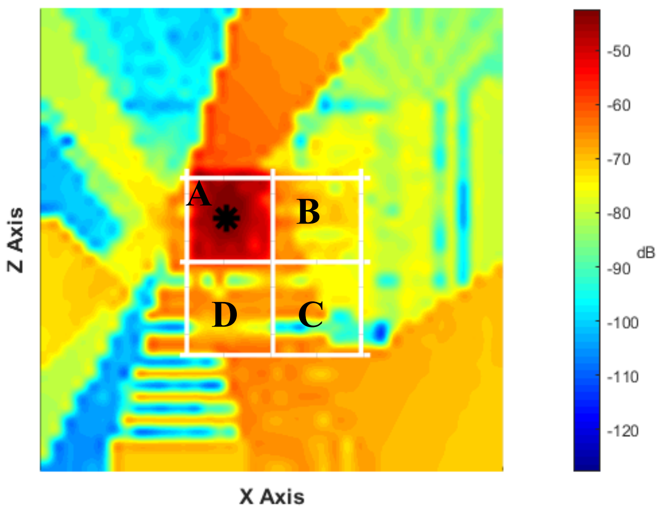

Figure 7 - Vertical plane cut at Y=10 (4 rooms).

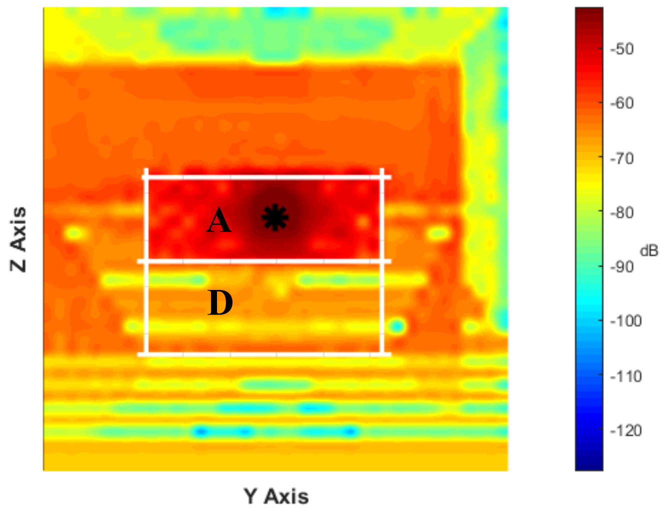

Figure 8 - Vertical plane cut at X=-8 (2 rooms).

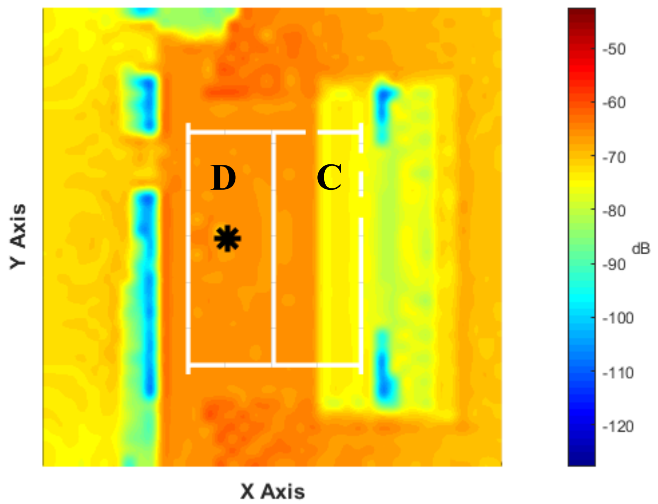

Figure 9 - Horizontal plane cut at Z=2 (level 1).

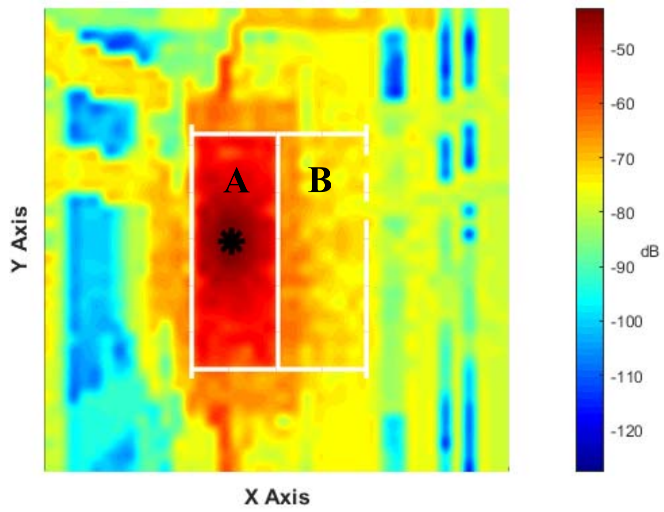

Figure 10 - Horizontal plane cut at Z=6 (level 2).