# Joint Ray Launching Method for Outdoor to Indoor Propagation Prediction Based on Interpolation

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*Abstract*—This paper proposes a novel model for predicting the outdoor to indoor radio signal coverage. This model is based on a joint ray launching algorithm that adapts different resolutions for outdoor and indoor simulations. The performance of the joint ray launching method is evaluated by a measurement at 3.5 GHz frequency. This model appears to be efficient for a scenario with mixed resolutions, in terms of both accuracy and computational cost.

Index Terms-propagation, outdoor to indoor, coverage prediction

## I. INTRODUCTION

From 3G networks onwards, the data service is increasingly important in network planning. The propagation prediction serves as an essential role in determining the quality of signal. To evaluate the coverage or interference from a macro site that is placed outdoors, it is necessary to predict the outdoor to indoor signal penetration.

The common difficulty in a combined scenario where both the coarse outdoor building model and the detailed indoor structure are presented, is the different resolutions to be considered during computation. Adopting an uniform resolution is not ideal due to the required level of accuracy for indoor and the computational cost for the size of outdoor environment.

The state-of-the-art propagation prediction models consist of several kinds. The empirical models are purely based on statistics or measurements. These are fast to implement but at a cost of precision. The deterministic models are time consuming while offering a higher level of accuracy. There are also some other propagation models known as semideterministic models that are categorised in between.

In [1], the intelligent ray launching method was initially proposed for outdoor scenarios. Later, the capability of the same model was again demonstrated by the indoor application in [2]. Moreover, a hybrid outdoor to indoor propagation model [3] was made possible by combining the outdoor ray launching and the indoor Finite-Difference Time-Domain (FDTD) model with a 5 cm uniform resolution.

In this paper, a new joint outdoor to indoor ray launching algorithm with mixed resolutions is presented.



Fig. 1: INSA Surroundings and Emitter Location

## II. ENVIRONMENT MODELLING

## A. Building Structure

The first step is to model the outdoor and indoor building structures based on the required level of detail. It is worth to mention that the outdoor buildings in the given example are 2.5D map data where each building is described by a 2D polygon shape and a height (Figure 1). The 2D polygons are extracted from Google Maps and the height of each building is measured by a laser meter [3].

The target building, however, should be properly modelled with a higher level of detail (Fig. 2). For example, the external windows [4] and internal walls need to be present in order to launch the rays at a finer resolution. In addition, the indoor floor plan is originally extracted from a 2D blueprint in \*.dxf format.

In this paper, both the outdoor and indoor building models have been reconstructed in the iBuildNet® software for a convenient implementation of the joint ray launching algorithm and are saved in a reader friendly XML-based format.



Fig. 2: INSA Indoor Floor Plan

TABLE I: Scenario Size and Material in Use

	Outdoor	Indoor
Size	300×400×30 m <sup>3</sup>	60×50×10 m <sup>3</sup>
Material	Concrete Heavy	Double Glazing Glass
		Plaster Board

## B. Building Material

The path loss of a ray propagating from one location to another relies on the Equation (1) in the ray launching algorithm [1]. Each reflection, diffraction or transmission yields additional attenuation, therefore the corresponding loss of each kind should be defined for all involved building materials.

$$Total Path Loss = L_{FreeSpace} + L_{Transmission} + L_{Reflection} + L_{Diffraction}$$
(1)

In this paper, each type of plane is assigned with a predefined material property. In the shown indoor structure (Fig. 2), the external windows and internal walls are set as double glazing glass and medium plaster board respectively. For outdoor scenario, each plane of the 2.5D building is modelled with heavy concrete material that incurs greater attenuation than the indoor internal walls. Furthermore, the dimensions and materials of both scenarios are summarised in Table I.

## C. Equipment Modelling

Based on the description in [3], the emitter is attached to the window of the opposite building at a height of 5.6 meter above ground, operates at 3.5 GHz frequency and has parameters of 0 dBm TX power, 10 dBi gain and an azimuth of 50°. In addition, the 3D antenna pattern, required by the ray launching algorithm, is constructed by the 2D horizontal and vertical patterns that have  $38^{\circ}$  and  $45^{\circ}$  of half-power beam width respectively [6]. The above parameters are also summarised and shown in Table II.

## III. SIMULATION AND RAY INTERPOLATION

#### A. Propagation Simulation

The ray launching algorithm is configured at a relatively high setting that allows maximal 7, 7 and 4 times of transmission, reflection and diffraction respectively. The path loss of a

TABLE II: Emitter Configuration

Frequency	3.5 GHz	
TX Power	0 dBm	
Antenna Model	ETS-Lindgren 3115	
Antenna Type	Horn Antenna	
TX Gain	10 dBi	
HPBW (V, H)	38°, 45°	

ray is calculated with an upper limit of 175 dB, which indicates a ray will be stopped from propagating once its accumulated path loss exceeds the threshold.

The ray launching algorithm is initialised outdoors from the emitter location with a resolution of 2 meter per cube. The next step is to capture the rays surrounding the target building, specifically the red contour around the building as shown in Fig. 1.

To continue the propagation in the indoor scenario with a ten times finer resolution (20 cm per cube), the rays surrounding the building have to be interpolated. Otherwise, the insufficient number of rays will degrade the precision of ray launching method and yield an incorrect coverage prediction.

#### B. Ray Interpolation

To better explain the collected rays surrounding a target building, a 3D plot (Fig. 3) has been drawn in MatLab® and assists to visualise the rays by indicating their heading directions. It should be noted that, in the given 3D plot, the different angles of arrival and elevation of the collected rays from a single sample point are resulted from the reflections and diffractions during outdoor simulation. However, only those rays that will penetrate through the outer boundary of the target building in further propagation, have the impact on the indoor simulation. In this case, an additional filter can be applied to abandon the rays that propagate away from the building. Moreover, the attenuations across different floors of a building are usually over 30 dB [9]. If the assumption is made that the cross-floor losses are large enough to invalidate the signals from outdoor, then only those rays that will penetrate through the outer boundary of target floor, have the impact on the indoor simulation and thus need to be interpolated.

The ray interpolation is based on two main factors. The ratio between two different resolutions and the heading directions of the rays. Each of the collected rays is then replicated at each node of the mesh square that is normal to its heading vector. An example of interpolation with 2:1 mesh square is illustrated in Fig. 4. A similar approach was developed in [10], in which article to maintain a constant spatial resolution or density, rays are periodically split into new rays while propagating away from the source location. The authors share the same concept to minimise the loss of precision resulting from low spatial resolution. However, the ray splitting [10] is rather an essential method to maintain a ray density continuously during a complex indoor propagation and requires recurrent splitting. The ray interpolation in this paper, replicates by a given resolution ratio, only part of the rays surrounding a building in an outdoor scenario.



Fig. 3: Rays Surrounding the Building with Heading Directions



Fig. 4: Ray Interpolation

TABLE III: Performance Summary

	Joint Ray Launching		Hybrid IRLA/FDTD	
Scenario	Outdoor	Indoor	Outdoor	Indoor
Resolution	2 m	20 cm	5 cm	5 cm
Preprocessing	0 s	10 s	0 s	41 s
Simulation	3 s	15 s	58 s	57s
RMSE(/ME)	8 dB	3.986/-0.001 dB	8 dB	2.39/0.09 dB

## IV. EVALUATION

In [3], the measurement campaign was carried out to verify the hybrid model. In this paper, the same measurement at 3.5 GHz frequency has been used for performance evaluation.

The proposed joint ray launching algorithm is applied to this environment and its simulation performance is presented as below.

## A. Computation Time and Memory Usage

The calculations were carried out on a PC with Intel Core i7-4770 CPU and 12 GB RAM. Multiple simulations have shown that the execution time is less than 3 seconds for outdoor at 2m resolution and under 15 seconds for indoor at 20cm resolution. The memory consumption for the joint scenario has a total of 41 MB. It should be noted that the overall size of the indoor scenario is slightly enlarged by 4 meters at each side in order to cover the space where the collected rays are located and only the target floor is considered during indoor simulation. Furthermore, the computation also benefits from the parallel capability [5] of the ray launching algorithm.

In contrast, under an identical configuration, several simulations with an 1 meter uniform resolution were implemented and took an average of 4 minutes and 700 MB memory to complete. According to the comprehensive comparison [8] between different resolutions for the ray launching algorithm, it is important to notice that a reasonable non-linear projection will indicate the lack of a considerable amount of memory for resolutions finer than 1 meter in our case. An attempt of 0.5m uniform resolution was made with large memory support and ceased when the memory consumption reached 4 GB. It is therefore worth to mention that a direct comparison between the hybrid model [3] and the proposed model may not be fair due to the different resolutions being taken in the indoor scenario, though, the execution time and accuracy of both models are summarised in Table III. Nevertheless, the effectiveness of the joint ray launching algorithm is reflected by both the low computational cost being stated above and the accuracy to be discussed in the following section.

$$RMSE = \sqrt{\frac{1}{N_p} \sum_{i=1}^{N_p} (M_i - S_i)^2}$$
(2)

where

RMSE = Root Mean Square Error

 $N_p$  = Number of Measurement Points

- $M_i$  = Measured Signal Strength of the  $i^{th}$  Point
- $S_i =$  Simulated Signal Strength of the  $i^{th}$  Point



Fig. 5: Joint Outdoor to Indoor Coverage Prediction (Indoor)

#### B. Calibration and Accuracy

The predefined materials serve as a guideline and are not recommended for research purposes. The importance of material calibration for a deterministic model has been stated in [7]. Similarly, to calibrate the reflection, diffraction and transmission losses of all the involved materials, a single simulation has to be carried out and the path information for all receiver locations (or measurement points) are recorded. Simulated Annealing (SA), as one of the popular metaheuristic methods, is then implemented to optimise the material properties towards the cost function as shown in the Equation (2).

The calibration is implemented with the 3.5 GHz measurement data from [3]. After the calibration with a total of 99 measurement points (72 outdoors and 27 indoors), the RMSEs between the simulation and measurement reached 8 dB and 3.99 dB respectively for outdoor and indoor. A 2D horizontal cut of the indoor coverage prediction is plotted in Fig. 5, from which the signal levels of rays passing through the external windows indicate that the wall openings [4] have been effectively taken into account. In addition, the comparison between the measured and simulated received signal strengths for indoor scenario is given in Fig. 6 and shows a -0.001 dB ME and the 3.986 dB RMSE. Furthermore, a top view of the joint outdoor to indoor coverage prediction at the level of indoor scenario is seamlessly presented in Fig. 7.

## V. CONCLUSION AND FUTURE WORK

This paper proposed a full 3D joint outdoor to indoor ray launching algorithm and the performance has been evaluated via the INSA scenario [3]. The proposed model has demonstrated its low computational cost and a high level of accuracy in predicting the outdoor to indoor signal coverage. In future, we would like to verify other outputs such as angle of arrival, angle of departure and delay spread. In conjunction with an indoor to outdoor propagation model in another research proposal, we aim to develop a robust and accurate mechanism that enables multiple transitions between outdoor and indoor for the ray launching algorithm.



Fig. 6: Comparison Between Measurement and Simulation



Fig. 7: Joint Outdoor to Indoor Coverage Prediction

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