Intelligent Ray Launching Algorithm for Indoor Scenarios

Zhihua LAI[1], *Guillaume De La ROCHE*[2], *Nik BESSIS*[2,3]
Pierre KUONEN[4], *Gordon CLAPWORTHY*[2], *Dibin ZHOU*[5], *Jie ZHANG*[6]

[1]Ranplan Wireless Network Design Ltd., Suite 25, The Business Competitiveness Centre, Kimpton Road, Luton, Bedfordshire, United Kingdom, LU2 0SX
[2]Institute for Research in Applicable Computing, University of Bedfordshire, Park Street, Luton, Bedfordshire, United Kingdom, LU1 3JU
[3]University of Derby, Kedleston Road, Derby, Derbyshire, United Kingdom, DE22 1GB
[4]GRID and Ubiquitous Computing Group, University of Applied Sciences of Fribourg, UCH-1705 Fribourg - Switzerland
[5]College of Information Science and Engineering, Hangzhou Normal University, China, 310036
[6]Dept. of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield, United Kingdom, S1 3JD

zhihua.lai@ranplan.co.uk, guillaume.delaroche@beds.ac.uk, n.bessis@derby.ac.uk, pierre.kuonen@hefr.ch, gordon.clapworthy@beds.ac.uk, dibinz@zju.edu.cn, jie.zhang@sheffield.ac.uk

Abstract. *This article describes the indoor IRLA (Intelligent Ray Launching Algorithm), which originates from an efficient outdoor propagation prediction model. Implementation and validation are given in detail. An indoor office scenario is selected and simulations via the IRLA model and two other reference models have been performed. Predictions are analyzed and recommendations are given. Results show that the indoor IRLA model is suitable for indoor wireless network planning and optimization process.*

Keywords

Intelligent ray launching algorithm, radio wave propagation prediction, indoor scenarios, path loss models, in-building network planning.

1. Introduction

Radio wave propagation prediction modeling has become increasingly important in wireless network planning and optimization [1] [2] since the emergence of 3G networks. The propagation predictions serve as a fundamental output for the advanced analysis and optimization such as capacity and link budgets etc. The identification of QoS (Quality of Services) or weak signal spots are based on the estimation of propagation prediction. At present, in order to build an efficient indoor DAS (Distributed Antenna System), the candidate antennas need to be tested and the possible combination is evaluated, which will give an optimal solution for indoor antenna placement. The solution is based on propagation prediction modeling because the minimal coverage ratio has to be considered.

Currently, radio wave propagation models consist of two kinds: small-scale and large-scale. On the one hand, small-scale propagation prediction deals with fast fading (i.e. the variation of signal strength over a short period of time such as one wavelength). For example, Rice fading distribution has been used to model the LOS (Line-of-Sight) case while Rayleigh fading distribution is being used widely in NLOS (None-Line-Of-Sight) [3]. On the other hand, the large-scale propagation prediction computes the average signal strength over a longer period of time. In this case, the predictions will give path loss based on (1):

$$\mathrm{PL} = P_{\mathrm{Rx}} - P_{\mathrm{Tx}} \quad (1)$$

where P_{Rx} represents the signal strength (dBm) at the location of the receiver and P_{Tx} represents the signal strength (dBm) at the location of the transmitter.

The modeling of large-scale radio wave propagation in indoor environments plays a crucial role in the investigation of 3G/4G network planning applications (such as localisation). In indoor environments, there are usually more irregular objects and material types, which make modeling much more complex, compared to outdoor environments.

Many outdoor large-scale propagation models such as [4] are accelerated based on the simplification that outdoor buildings are 2.5-D polygons with flat roofs. However, as objects in indoor environments can be of any shape and in any position, such as lamps hanging at different heights, etc. Indoor radio wave propagation predictions are usually more challenging because these irregular objects impact greatly the indoor propagation characteristics (such as fast fading).

In general, large-scale propagation models fall into two kinds: empirical and deterministic. Empirical models are mainly based on empirical factors such as distance or frequency. They are computational fast but they do not consider much environmental information so their accuracy is limited. For example, the ITU (International Telecommunication Union) Model for Indoor Attenuation [5] is based on a single equation and the path loss prediction is valid only for frequency ranging from 900 MHz to 5200 MHz and floors from 1 to 3. Similarly, LAM (Linear Attenuation Model) [6] relies on measurement data, based on which a linear equation can be built. On the other hand, deterministic approaches take into account the environmental information such as object positions and the corresponding materials. Generally speaking, these approaches are more time-consuming compared to empirical models but a higher level of accuracy can be obtained. For example, in [7], the authors propose an accelerated dominant ray-based method for indoor scenarios. Despite many acceleration techniques such as [8], [9] and [10], the use of accurate propagation modeling for indoor scenarios remains limited due to the complex indoor propagation environment.

Apart from these two categories, some propagation models consider both empirical and deterministic factors, which are categorized as semi-empirical (or semi-deterministic) approaches. For example, MOTIF [11] can be considered as a semi-deterministic approach that includes stochastic factors and deterministic computation. Such models usually perform faster than deterministic approaches such as ray tracing and their accuracy is high in some scenarios. For example, MOTIF is limited in 2-D scenarios.

Ray-based methods can be categorized as deterministic approaches. They are widely used in propagation prediction. Compared to FDTD (Finite Difference Time Domain)-like methods [12], they consume less memory and are far more efficient. These ray-based methods compute the possible rays between the emitter and receivers in complex environments and they need to search the rays to compute reflections and diffractions, based on Descartes' laws. Hence, they tend still to be very time-consuming if the environment is complex, i.e., if there are a large number of obstacles. Usually, the accuracy of ray-based methods is limited by the number of rays that can be computed within a reasonable time.

Different methods to accelerate ray-based methods are proposed in the literature. For example, in [8], a preprocessing stage is required to compute the visibility tree between obstacles and in [7], the authors propose a dominant path model which only computes the few rays that comprise of the ones that give the most contribution. Depending on the ways of computing the rays, ray-based methods can be further categorised into ray tracing and ray launching. On the one hand, ray tracing computes the rays backwards from the receivers. For example, the reflection ray can be computed by: (a) mirroring the receiver at the targeted facet, (b) computing the intersection point between line segment from transmitter to the mirrored point and the facet, (c) launching the reflection from the intersection point to the receiver direction. Ray tracing gives precise rays between a transmitter and a receiver and is thus suitable in point-to-point scenario where there are only a few receiver locations of interests. However, if the number of prediction locations is considerably large, ray tracing will suffer from a long running time, especially in scenarios where there are many complex obstacles which will incur more data-intensive operations such as intersection tests. Besides, ray tracing treats the calculation of neighbor pixels equally the same i.e., the computational time is roughly linearly proportional to the number of receiver locations.

In contrast, ray launching computes the rays from the emitter. Ray launching is an image-sampling method which uses discrete rays by an angle. Inevitably, gaps will be created gradually after the rays undergo reflections and diffractions. In order to solve this problem, a reception sphere [13] can be used to capture the missing rays. More rays can be launched to improve the accuracy but this will slow down the computation. In general, ray launching walks through the rays and computes the reflections, transmissions and diffractions iteratively. The pixels gain experiences from its previous pixels along the same path, which is faster than ray tracing. Ray launching is suitable in point-to-many scenarios, such as coverage prediction. The ray launching may be more suitable for wireless network planning and optimisation in indoor scenarios because generally it is computationally more efficient than ray tracing and it provides a relevantly acceptable level of accuracy.

1.1 Related Work and Contribution

The authors have originally developed the IRLA model for outdoor scenario [2]. In [14] and [15], the authors proposed and implemented the parallel IRLA based on POP-C++ (Parallel Object-oriented Programming in C++) [16] and a performance speed up was observed. In [17], the IRLA model was improved by smart algorithms to solve angular dispersion of ray launching and thus the accuracy is improved. In [18], the authors extended the IRLA model to indoor scenarios and it has been validated by the measurement campaign proposed in [19]. The results show that the indoor IRLA model is promising because it is capable of providing accurate results within a short amount of time. In [20], the authors further combine the IRLA model with a FDTD-like method: MR-FDPF (Multi Resolution Frequency Domain ParFlow) [21] for an indoor to outdoor scenario where the accuracy was validated by the measurement campaign. In [22] and [23], the authors combine the IRLA model with MR-FDPF for outdoor to indoor scenarios. Based on the aforementioned work on the IRLA model [24], This article will contribute by providing:

- Details on the calibration of the indoor materials.
- A simplified 2.5-D indoor IRLA model.
- Simulation results that are compared with two referenced models: MR-FDPF [21] and COST231-Multi Wall [25].

The rest of the article is organised as follows. First, the outdoor model IRLA [2] [14] will be briefly described. Next the details will be investigated to make this model suitable for indoor scenarios. The modified 2.5-D IRLA model for indoor scenarios will also be presented. The calibration of materials will be described. Next an indoor measurement campaign will be described, which is used to validate the model. Performance (such as speed, accuracy) will be analysed by contrasting the results obtained via MR-FDPF and COST231-Multi Wall models. The comparison between the 3-D and 2.5-D IRLA models are also discussed with recommendations given and finally, the future prospectives are described, which concludes this article.

2. IRLA Model

The idea of the IRLA model is based on the discrete ray launching algorithm. The input to this model relies on the creation of a 3-D discrete data set which contains the vector building data, material items associated to each obstacle, and the discrete data set made given a defined resolution. Finally, the basic unit of the discrete data set contains the property values (such as edge or corner) and index to the object list. Each object list stores the polygon coordinates and index to the material table. The IRLA model traces the rays from the emitter and by adopting the techniques proposed in [17], the angular dispersion of discrete ray launching is eliminated.

The outdoor IRLA model [2] comprises three main components: LOS (Line-of-Sight), VD (Vertical Diffraction) and HRD (Horizontal Reflection and Diffraction). The LOS component deals with visibility pixels, collecting direct paths from emitter and most importantly the secondary pixels for the use of VD and HRD. Mathematically and reversely, the VD component calculates the dominant multiple roof-top diffractions by a fast pixel checking principle that draws the shortest edges between the emitter and receivers. The HRD component performs the actual 3-D ray launching. The rays are abandoned when they hit the roofs due to the fact that there seldom exist dominant rays which are a combination of vertical and horizontal planes [4]. The IRLA model for outdoors has been tested to show suitability (in the aspects of both speed and accuracy) in use for wireless network planning applications [24] and the inherent principle of IRLA is easily parallelizable. In [14], a parallel implementation of IRLA via POP-C++ (Parallel Object Oriented Programming in C++) has been presented and performance is evaluated.

2.1 3-D IRLA Model

In [18], the IRLA model was first extended to the indoor scenario. Modifications of the outdoor IRLA model were made. First the component VD has to be eliminated from the indoor IRLA model because it is not applicable to the calculation of vertical diffractions in indoor scenarios. Instead, the indoor IRLA component of HRD is enhanced by also calculating vertical diffractions. The LOS and HRD components are kept as two fundamental components with slight modifications. It is known that ray launching suffers from the angular dispersion problem because ray launching is a sampling method which launches the rays that are separated by an angle. Both components are optimized via a new approach proposed in [17] to solve the angular dispersion of ray launching. Rays are collected and the multipaths are obtained and hence channel characteristic such as PDP (Power Delay Profile) can be simulated. The process of IRLA prediction for indoor scenarios starts with launching rays in all 3-D directions. Based on the discrete data set, the resolution and the number of cubes along each dimension (X, Y and Z) are known. Therefore the number of discrete rays required can be obtained by connecting the emitter to all the cubes at the fringe of the scenarios [17], which can be found in (2):

$$N = 2N_xN_y + 2(N_z - 2)(N_x + N_y - 2) \tag{2}$$

where N is the number of discrete rays and N_x, N_y, N_z are the number of cubes in dimension X, Y and Z respectively.

This ensures that no pixels are missing due to angular dispersion of ray launching [17] from the LOS component. The principle is useful in distribution of rays, e.g. in parallel. The secondary cubes collected in component LOS serve as input to the HRD component, which iteratively follows the discrete rays. Rays disperse as they propagate, which causes coverage gaps. To solve this, an intelligent procedure is proposed in [17], which dynamically accounts for rays that fill the gaps. Material indices are recorded within each cubic entry and applied to discrete rays that are being followed. Based on a few measurement locations, the material values are calibrated once and applied to predictions.

2.2 2.5-D Modification of IRLA

In-building deployment usually involves planning and optimization of a multi-floor building in indoor DAS. Thus, the predictions obtained from the indoor IRLA model need to account for the propagation characteristics such as transmission between floors, and the use of a discrete data set may not be so efficient if the scenario is large (such as a skyscraper) and the resolution is fine-grain.

It has been observed that the radio wave signal strengths drop dramatically when they undergo a few transmissions through different floors. The trade-off between speed and accuracy thus may be based on the assumption that the signal strength affects a maximum of n ($n >= 1$) floors, including the floor on which the emitter resides. Thus, discrete data sets for each floor can be created individually and combined during runtime in each prediction, which consumes less memory and improves the efficiency.

In order to develop a propagation model suitable for indoor DAS planning and optimisation process, the 2.5-D IRLA model for indoor scenarios can thus be proposed based on the following.

- The LOS component accounts for 3-D LOS rays and corresponding antenna pattern values are estimated and added.
- The HRD component computes the NLOS rays in the horizontal plane in order to improve the efficiency.

- Similarly to the outdoor VD component, the 2.5-D indoor IRLA model employs a VD component that cuts vertically to the indoor scenario which accounts for the vertical diffraction rays.

In order to validate the 2.5-D indoor IRLA model, the following section will describe an indoor scenario. The measurement was conducted and compared to four models: the 3-D IRLA model, the 2.5-D IRLA model, the MR-FDPF model and the COST231 Multiwall model, respectively.

3. Experiments

3.1 Scenario

Propagation models need to be validated by measurements for the accuracy. The comparison analysis can aid the improvement of the propagation models. In order to validate the IRLA model, an indoor office (Fig. 1) has been selected as the indoor testbed. The office has three rooms and is located on the first floor. There are 255 polygons and more than 1000 vertices all together. The dimension for this scenario is $16 \times 9 \times 4$ (m^3). The materials found in the scenario include: Glass, Wood, Metal, Plastic, and Concrete. As shown in Fig. 1, there are cubicles in the middle, which is a challenge for 2-D propagation models because in reality the radio wave signals travel in vertical directions (such as diffractions on the edges of desk).

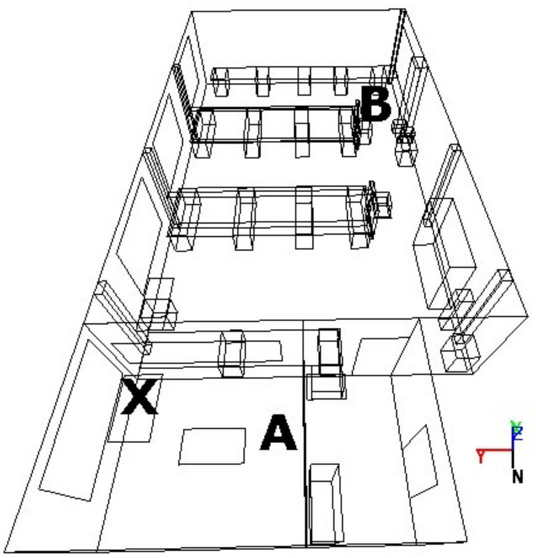

Fig. 1. Indoor office; 'X': emitter; 'A': LOS, 'B': N-LOS.

3.2 Measurements

The emitter is a 3.525 GHz signal generator (power 6 dBm) with an omni-directional antenna (gain 2.8 dBi, EIRP Equivalent Isotropically Radiated Power 8.8 dBm). This frequency has been selected in order to study WiMax indoor base stations. The emitter is located on the table (1.35 meter height) in the meeting room (see Fig. 1) and measurement locations (0.98 meter height) are positioned by the grid pattern on the floor (see Fig. 2). This helps recording positions without an indoor GPS (Global Position System). To avoid as much signal variation (e.g. due to noise disruption) as possible, a measurement campaign is carried out when there are few people in the room. To avoid the interference of human bodies when manually triggering the spectrum analyzer, the measurement data of the first few and last few points are removed. Several measurement snapshots are taken to average the final signal strength. Around 200 measurement locations gridded by 0.5-meter-square [19] at ground-level 1.5 meter height are chosen. The measurement techniques and the removal of human body influence are detailed in [19].

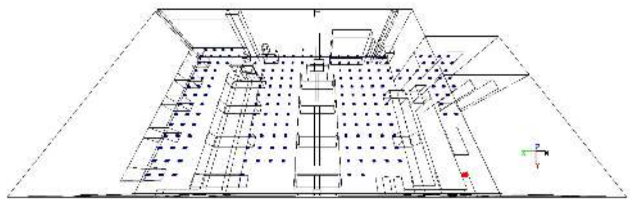

Fig. 2. Measurement locations, positioned by grid pattern on the floor.

3.3 Calibration

It is not possible to know exact properties of materials in every scenario. Therefore, a calibration process is needed to adjust the properties of materials (such as conductivity). The IRLA model provides the calibration process to make the simulations fit into reality. A first run with defaulted parameters of materials is performed and the multipaths associated to each measurement locations are obtained. Based on the multipaths, the calibration process can be performed.

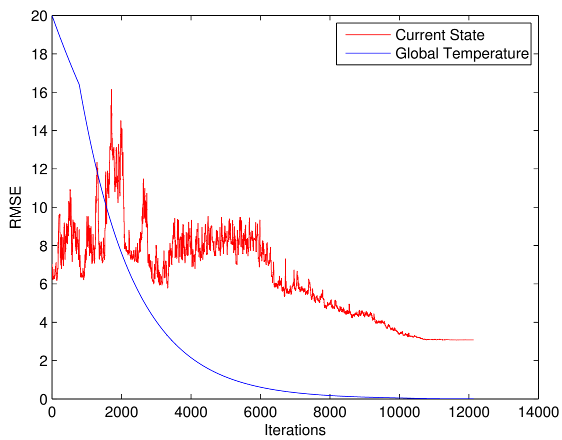

Fig. 3. Calibration of the IRLA model based on simulated annealing.

The 3-D path loss matrix can also be obtained by the first run of IRLA. To make it even more efficient, only selected layers (locations) can be considered. Multipaths information for selected locations are computed. With this information, channel characteristics can be investigated. However, since the IRLA model computes the rays from the emitter, the requirement for multipath data does not incur extra overheads since this can be easily recorded together with the path loss. To improve the accuracy of the model, a calibration of the parameters, based on an SA (Simulated Annealing) approach, was implemented in [2] where the RMSE (Root Mean Square Error) between the simulation and the measurement is minimised. The calibration is based on the multipaths i.e., one single IRLA simulation has to be performed and all the rays are stored in memory.

The material parameters to be tuned can be considered as a vector v. At each iteration of SA, v is adjusted and the fitness is evaluated. Based on a probability, the v is accepted. The SA approach converges to an sub-optimal v finally (Fig. 3). The use of multipaths avoids rerunning the simulation at each iteration of SA, because the fitness value can be computed based on the multipath reached at each measurement location.

4. Performance Evaluation

The indoor scenario described above (Sec. 3) is used to validate the IRLA model. This section introduces the calibration process of the IRLA model and experimental results. Based on the prediction, comparisons can be investigated and recommendations are given.

4.1 IRLA Validation

A single run using a standard PC (2.5 GHz CPU, 4 G RAM) with this scenario takes around 1 minute for the computation of the 3-D path loss and multipaths information. The SA calibration takes around 2 minutes to complete and v is obtained. The default parameters yield around 6 dB RMSE (Figs. 4 and 5) on the first run. It can be observed that there are some prediction points that are of large differences. This could be caused by the following:

- The materials and other network parameters (such as path loss coefficients) are not calibrated.
- The measurement data itself may be affected by many factors such as the variation of environment (such as moving vehicles).
- The IRLA model may terminate the ray computations at the early stage if the rays carry weak signal strengths due to incorrect summation from uncalibrated materials.

After proper calibration, the prediction results compared to measurements show an agreement (Tab. 1), with the 3.5 dB RMSE and a mean error of 0.01 dB.

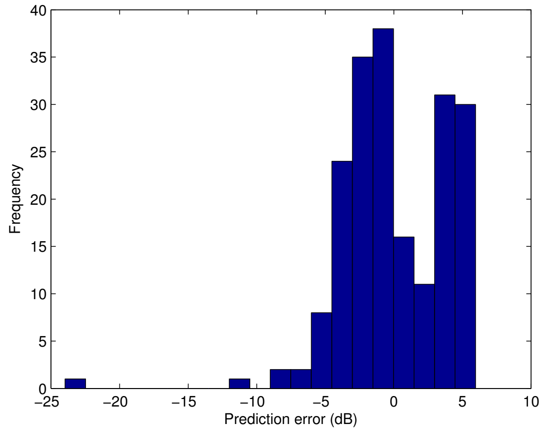

Fig. 4. Error in dB before calibration: RMSE 6 dB.

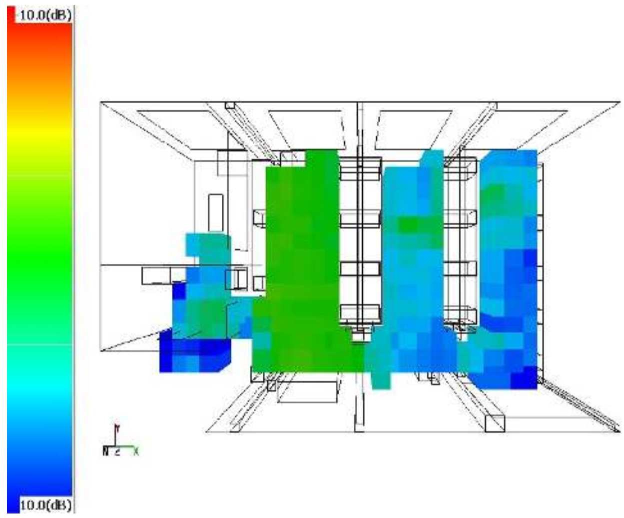

Fig. 5. Prediction errors (dB).

	Uncalibrated	Calibrated
RMSE (dB)	6	3.5
Mean (dB)	3.2	0.01

Tab. 1. Calibration of 3-D IRLA.

It can be observed that most predictions are accurate within the ranges of $[-10, +10]$ dB difference. There are few points that prediction tends to be either too optimistic or pessimistic. From Fig. 5, the prediction errors can be visualised geographically. It can be seen that the most optimistic predictions are distributed within a short distance range from the emitter and receivers (such as the locations near by the refrigerator or behind the door). The pessimistic prediction points are located far from the emitter. This may be used as important evidence to further optimize the model.

4.2 Comparison with Reference Tools

In this section, the 2.5-D and 3-D IRLA model will be compared with two reference models: MR-FDPF and COST231 Multiwall.

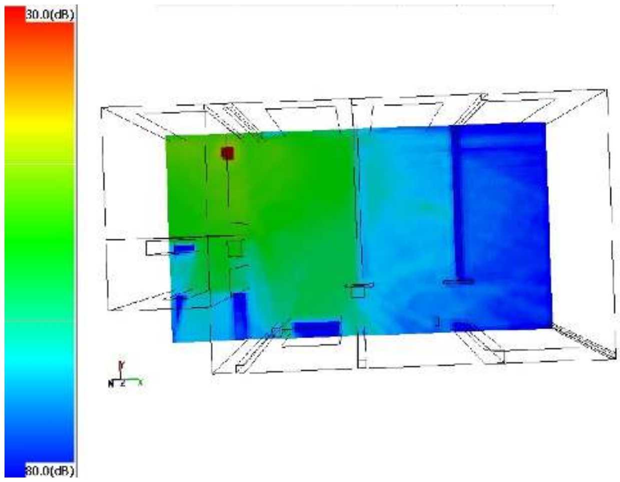

Fig. 6. Coverage prediction after calibration.

4.2.1 MR-FDPF Model

MR-FDPF [21] is a FDTD-like method but in the frequency domain. MR-FDPF (Multi-Resolution Frequency Domain Parflow) is based on the ParFlow model derived in [26]. It is a finite difference approach similar to finite difference time domain method (FDTD) which has the advantage of being able to compute all the reflections and diffractions without limitations since it solves the Maxwell's equations [27].

The formulation of ParFlow is based on the transmission line matrix (TLM) method. In this approach (in 2-D) the field is modeled by four flows corresponding to the four cardinal directions. In each pixel, also referred to as a node, scattering matrix is associated which efficiently models reflection and diffraction effects.

The advantage of ParFlow compared to FDTD is that the four fields are scalar, thus reducing the number of variables (no E and H fields). In [26] a frequency domain implementation of ParFlow was proposed. The advantage of this formulation is that the steady state of the source can be computed using a recursive formalism, instead of solving the equations for the whole environments. Therefore, a multi-resolution approach is used where the nodes are gathered into multi resolution nodes (MR-nodes) and where the problem is divided into sub-problems, thus highly reducing the overall complexity (mainly due to the need for inversion of large matrices).

The MR-FDPF algorithm works into two steps. First, a pre-processing phase where the environment is divided into MR-nodes and where the scattering matrices are computed. This phase does not depend on the sources to simulate but only on the scenario. Therefore it only has to be performed once. The second step is the propagation phase which works on the boundary conditions: A source is recursively included in larger space blocks up to the full space, and the backward propagation is done by propagating incoming boundary flows toward the separation line and down to the unitary cells.

The advantage of MR-FDPF is that, due to the multi-resolution approach, the computational phase of the propagation of one source is very low compared to a time domain implementation. However, when moving to 3-D implementations, the number of flows to compute increases and in such case the frequency domain implementation has no obvious advantages in term of complexity. Therefore this model is usually restricted to 2-D.

In [28] MR-FDPF was successfully used for indoor network planning and it was shown that, when considering flat environments where the main propagation effects are in the horizontal plane, it was possible to reach very high accuracy. Moreover, a calibration of the method was also proposed to compensate for these 3-D effects by changing the parameters of the materials. The method was also extended to simulate larger bandwidth, more details can be found in [29]. Due to its accuracy, MR-FDPF is included in a Wifi network optimization tool [30].

MR-FDPF has lower complexity than FDTD because of its pre-processing and it directly solves the final Maxwell equations without time information. At this stage, 2-D MR-FDPF is usually tested due to much larger computational complexity requirement when this model is applied in the 3-D cases. In order to use MR-FDPF to predict this indoor scenario, some assumptions have to be made. First a cut on receiver locations from full 3-D data is required. However, a 2-D scenario does not fully reflect the 3-D characteristics by approximation of one cut. For example, a table not blocking rays may be a reflected source, which is difficult to model in 2-D. Fortunately, by calibration, similarly to the IRLA model, 2-D MR-FDPF can adjust the material properties so that the accuracy can be improved. For example, rays transmitted by a window do not attenuate much but this will be treated as a heavy-thick wall in this 2-D scenario used by MR-FDPF. By calibrating with measurements, this material is adjusted.

4.2.2 COST-231 Multiwall Model

COST-231 Multi Wall [25], is a semi-empirical indoor model, which only accounts for the attenuations for walls and floors. Therefore, it does not compute reflection or diffraction rays. The only output from this model is the path loss/power prediction, which is an estimation based on the material properties and the number of transmitted walls/floors. This model is computationally efficient and it does not require pre-processing. The running time of the Multi Wall model is usually less than a few seconds. The prediction errors tend to increase with the number of transmitted walls or floors. e.g. the COST231 Multi Wall model generally produces pessimistic results when the receiver locations are far from the emitter.

4.3 Comparison and Recommendations

Tab. 2 compares the prediction performance obtained via the IRLA (2.5-D and 3-D) model, the 2-D MR-FDPF model and the COST231 Multi Wall model. All simulation results are obtained after calibration. It can be observed that these models generally give a high agreement (cf. Fig. 10) between prediction and measurement. In a full 3-D scenario, at least in this indoor scenario, 2-D MR-FDPF relies heavily on the calibration without which, this model tends to give large prediction errors due to inaccurate modeling of materials. The accuracy before calibration for MR-FDPF is around 8 dB whilst this is dramatically improved to around 3.5 dB due to calibration of the materials. For example, the emitter is placed on a table and the table should be removed from 2-D cut, otherwise it will be treated as an obstacle in MR-FDPF model. On the standard PC (AMD 64+ Dual, 4 GB), the preprocessing for MR-FDPF takes around 3 seconds and the computation time is less than 1 second, which is fast in a small 2-D scenario. However, due to its 2-D characteristics, some important ray phenomenal in 3-D are not efficiently captured. For example, MR-FDPF treats the flows in only 2-D, as they only propagate in the 2-D plane. Rays bouncing by reflecting on the ceiling or floor are ignored. The accuracy obtained though MR-FDPF is 3.5 dB RMSE (0 mean error after calibration). The prediction via 2-D MR-FDPF is designed for power level/path loss only, which does not compute the delay information.

The 3-D IRLA model for indoors, as presented in this article, is fully applicable in 3-D scenarios in which the model is capable of capturing important 3-D dominant rays. Compared to MR-FDPF, the IRLA models (3-D and 2.5-D) do not require a preprocessing stage. However, since this is a full 3-D model, all levels of receiver locations are computed which requires longer computation time than 2-D MR-FDPF. The timing for the 3-D IRLA model, at least for this indoor scenario, is still within an acceptable range (less than 3 minutes) where it can be used to fully predict 3-D propagation mechanism such as PDP, DS. The accuracy before calibration via the 3-D IRLA model is around 6 dB by using standard parameters and this can be improved so that a similarly high accuracy can be obtained (3.5 dB RMSE). The 3-D IRLA model is not overly reliant on exact materials, whereas this is of critical importance in ensuring high accuracy for MR-FDPF models.

The 2.5-D IRLA model, computes the N-LOS rays in horizontal plane, which is less time-consuming than the 3-D IRLA model. The running time, compared to the full 3-D IRLA model, is shortened to less 10 than seconds in this scenario. The accuracy provided with the 2.5-D IRLA model is still acceptable, with the RMSE equal to 4.9 dB. Therefore, the 2.5-D IRLA model may be used as a compromise between speed and accuracy in indoor wireless network planning and optimisation.

Figs. 7 and 8 plot the rays generated by the 2.5-D and 3-D IRLA model. As 2.5-D IRLA only computes the NLOS rays in the horizontal plane, it is faster but does not consider diffractions rays or reflections rays in the vertical plane (such as ground reflection rays).

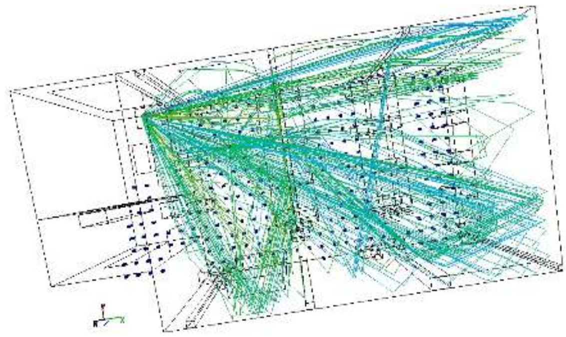

Fig. 7. rays generated in the 3-D IRLA model.

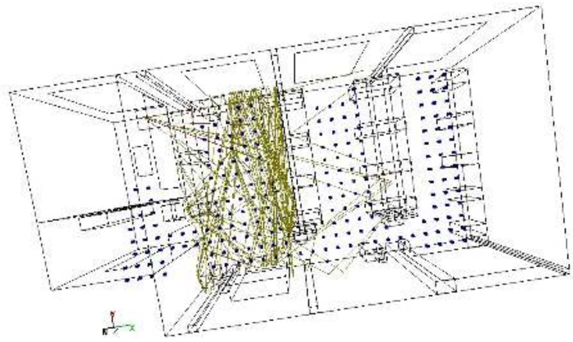

Fig. 8. rays generated in the 2.5-D IRLA model.

	3-D IRLA	MR-FDPF	Multi Wall	2.5-D IRLA
RMSE (dB)	3.5	3.5	5.6	4.9
Time (s)	< 60	< 5	< 1	< 10

Tab. 2. Performance comparison.

Fig. 9 plots the fitting curves of PDF (Probability Density Function) of prediction errors in dB. It can be seen that the 3-D IRLA model and MR-FDPF gives the highest accuracy (higher probability with small errors) while COST231 Multi-wall and 2.5-D IRLA models yield the similar accuracy in this indoor scenario.

The COST231-Multi Wall model [25], is extremely computational efficient and this model also does not require preprocessing. In this scenario, this semi-empirical model obtains high accuracy, which is mainly because there are few walls to penetrate. It is easy to calibrate with the losses for each wall and floors. Therefore, an agreement can be observed. However, the performance of this model is limited due to the absence of capturing reflection and diffraction rays. For example, in a corridor where diffractions dominate, COST231-Multi Wall model will fail. The running time for this model is usually less than 1 second, and the accuracy obtained generally depends on the scenarios.

By comparing these four indoor models, a recommendation for their use can be given. COST231-Multi Wall is efficient and is suitable for use when an estimation of indoor coverage is required on an less complex building structure such as the scenario presented in this article. MR-FDPF should have high accuracy because it incorporates radio wave propagation physics (a differential solver of Maxwell equations) but, as 3-D MR-FDPF is time and memory con-

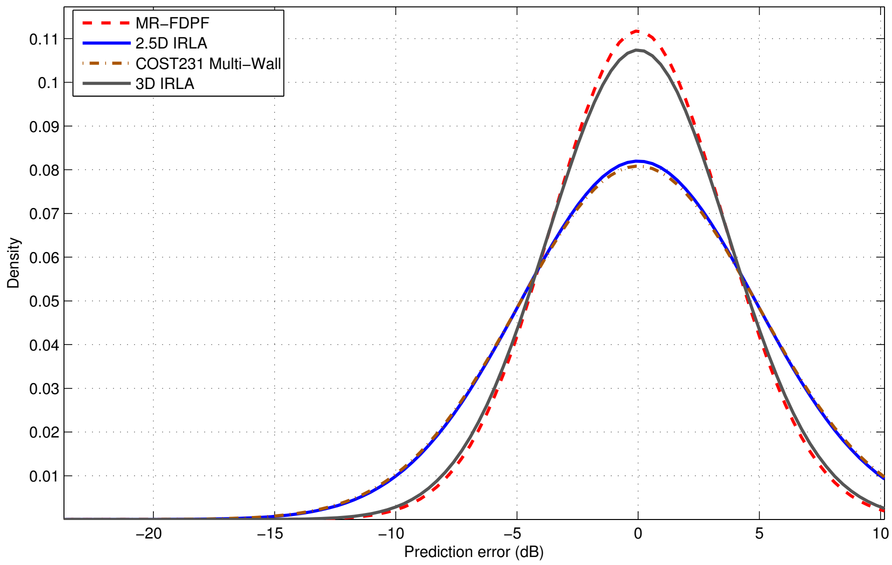

Fig. 9. Fitting curves of PDF of errors.

suming and still under investigation, the 2-D MR-FDPF is suitable only for indoor structures in which most propagation phenomena take place horizontally in the 2-D plane. Thus, it is not suitable in multi-floor propagation simulation, where a full 3-D model is required. However, 2-D MR-FDPF is capable of providing high accuracy on a floor after the calibration from measurements to correctly model the material properties. 3-D IRLA does not rely on calibration and is useful in prediction for multi-floor indoor structures or complex, large indoor areas. If there are no measurements, IRLA is preferred because it can be used to find coverage gaps which may not be practically feasible for 2-D MR-FDPF and COST231 Multi Wall models. The 2.5-D IRLA generally gives a high level of accuracy and multipaths (2.5-D NLOS rays and 3-D LOS rays). The advantage of using 2.5-D IRLA model is that it provides an acceptable level of accuracy but within a much shorter time than the full 3-D IRLA model. Therefore, the 2.5-D IRLA model is suitable in some indoor applications, such as DAS planning and optimisation.

5. Conclusion and Perspectives

This article describes an extended ray launching model, IRLA, which was originally designed for outdoor scenarios. A full indoor scenario (a typical office) is chosen to validate the performance of this model. Comparisons with several recommendations were made.

Compared with other models, the advantages of the 3-D IRLA model are:

- It offers an accuracy similar to existing deterministic tools.
- The full 3-D rays/prediction matrix are computed.
- It does not require preprocessing.
- It is fast compared to standard ray tracing methods.

Compared with the 3-D IRLA model, the advantages of the 2.5-D IRLA model are:

- The 2.5-D IRLA model is even faster, providing a similar execution speed to empirical models. Therefore it is possible to test many indoor network configurations within a short amount of time.
- The floor separation and horizontal NLOS rays computation further improve the efficiency and it may improve the efficiency of parallelism.

For example, further work includes the investigation of prediction errors in NLOS cases for some locations. It is also useful in validating the delay spread prediction via the IRLA model through measurements.

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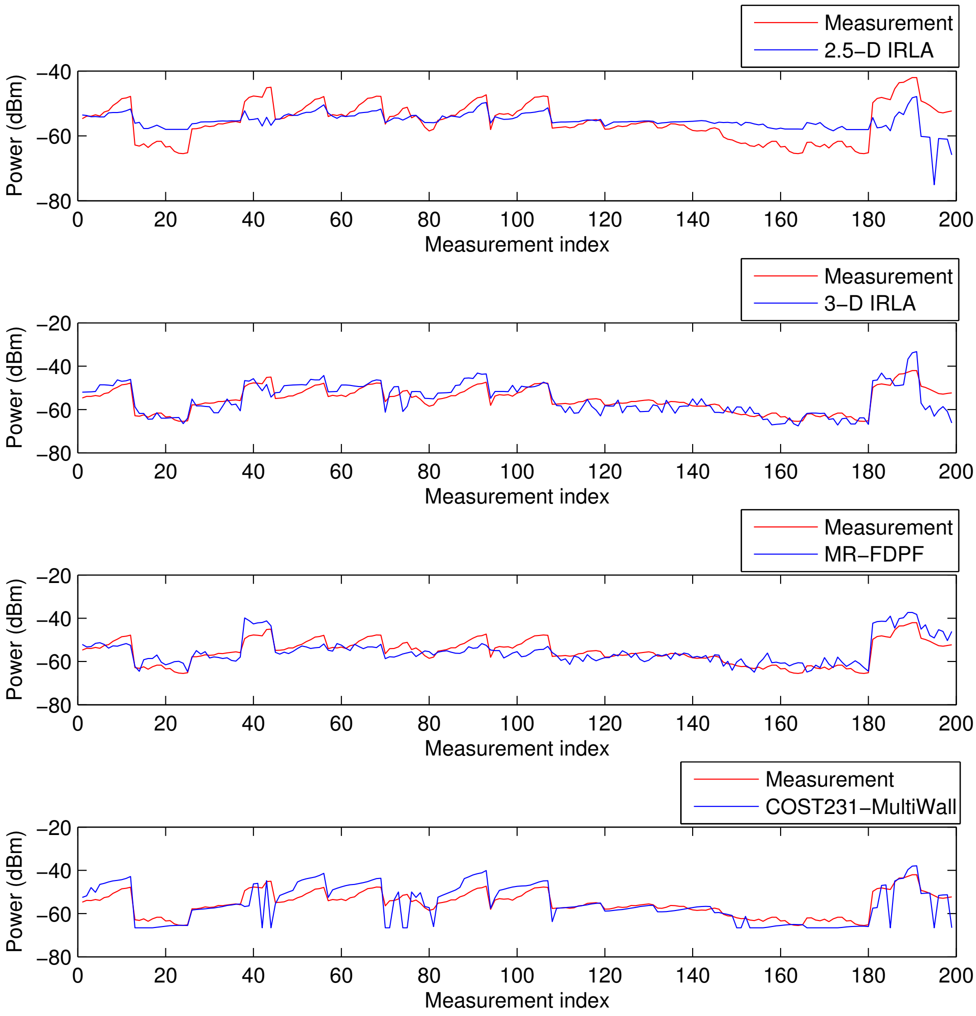

Fig. 10. Accuracy comparison.

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About Authors. . .

Zhihua LAI is a research fellow (since 2010) at Ranplan Wireless Network Design Ltd., United Kingdom. He completed a B.Sc. (Honours, First Class) and Ph.D. at the University of Bedfordshire in 2006 and 2010, respectively. He was also a visiting scholar at GRID and Ubiquitous Computing Group, University of Applied Sciences of Fribourg, Switzerland in 2009 when he developed parallel distributed radiowave propagation models. His main research interests include radiowave propagation modelling and distrbuted/parallel algorithms. He has published over 10 papers and has been involved in a number of funded European projects in these areas.

Guillaume DE LA ROCHE is a senior research fellow (since 2007) at the Centre for Wireless Network Design (CWiND), United Kingdom. Earlier he was with Infineon (2001-2002, Germany), Sygmum (2003-2004, France) and CITI Laboratory (2004-2007, France). He was also a visiting researcher at DOCOMO-Labs (2010, USA) and AxisTeknologies (2011, USA). He holds a Dipl-Ing from CPE Lyon, and a M.Sc and Ph.D. from INSA Lyon. He is the principal investigator of European FP7 project "CWNetPlan" on combined indoor/outdoor wireless network planning.

Nik BESSIS is the Head of Distributed and Intelligent Systems research group and a full Professor of Computer Science in the School of Computer Science and Maths, University of Derby, UK. Nik is also associated with the Department of Computer Science and Technology at the University of Bedfordshire, UK. His research interests include grids, clouds, crowds and collective intelligence. He is involved in and leading a number of funded projects in these areas. He has published 100 papers and 3 books, served as a committee member and a reviewer, a conference and/or workshop chair and the Editor-in-Chief of the International Journal of Distributed Systems and Technologies.

Pierre KUONEN obtained a Master degree in electrical engineering from the Swiss Federal Institute of Technology (EPFL) in 1982. After six year of experience in industry he joined the Computer Science Theory Laboratory at EPFL in 1988 and started working in the field of parallel computing. He received his Ph.D degree in 1993. Since 1994 he steadily worked in the field of parallel and distributed computing. First, at EPFL where he founded and managed the GRIP (Parallel Computing Research Group), then at the University of Applied Sciences Western Switzerland (HES-SO). Since 2003 he is a full professor at the HES-SO of Fribourg at the institute of Information and Communication Technologies (TIC) where he is leading the GRID & Cloud Computing Group.

Gordon CLAPWORTHY received a BSc (Honours, First Class) in Mathematics and a Ph.D. in Aeronautical Engineering from the University of London, and an MSc, with Distinction, in Computer Science from The City University, London. He is currently Professor of Computer Graphics in the Department of Computer Science & Technology and Head of the Centre for Computer Graphics and Visualization (CCGV) at the University of Bedfordshire, UK. He has nearly 200 publications, and his interests are medical visualization, computer animation, biomechanics, virtual reality, surface modelling and fundamental computer graphics algorithms. He is a member of ACM, ACM SIGGRAPH and Eurographics.

Dibin ZHOU is a research fellow (since 2010) in University of Bedfordshire, United Kingdom. He finished BSc and Ph.D. in Zhejiang University, China in 2002 and 2008 respectively. He has been a lecturer at Hangzhou Normal University since 2008. His main research interests include scientific data visualization and analysis, distrbuted/parallel algorithms, GPGPU programming.

Jie ZHANG is a Professor at the Communications Group, the Department of Electronic and Electrical Engineering, University of Sheffield (www.sheffield.ac.uk). Before taking the Chair in Wireless Systems at Sheffield in Jan. 2011, from 1997 to 2010, he had been with University of Bedfordshire, Oxford University, Imperial College London and University College London etc. His research interests are focused on radio network planning and optimisation. Since 2003, as the Principal Investigator, he has been awarded 17 projects worth over £4.0 million (his share) by the EPSRC, the European Commission (FP6/FP7) and the industry etc. He was/is a Co-Investigator of two EPSRC-funded projects on femtocell (B)4G mobile communications. Since 2006, he has published over 100 papers in referred journals and conferences, over 10 of which have been widely cited. He is an author of the book - “Femtocells: Technologies and Deployment” (Wiley, Jan. 2010).