

FDTD and Ray Optical Methods for Indoor Wave Propagation Modeling

Lajos Nagy

Abstract— Growing interest in providing and improving radio coverage for mobile phones and wireless LANs inside buildings has recently emerged. The need of such coverage appears mainly in office buildings, shopping malls in very complex environment. Although the three dimensional FDTD method has shown great promise, the calculation time is very environment dependent and exceeds the calculation time of ray tracing or ray launching in most cases. In this article, we focus on the theoretical estimation and comparison of FDTD and ray methods in aspects of the algorithmic complexity. We introduce measured and computed results for indoor environment to illustrate the time and memory requirement of 3D FDTD method. Finally detailed introduction of combination of Ray optical and FDTD methods is presented.

I. INTRODUCTION

Mobile and WLAN radio network optimal indoor coverage has recently emerged. The need of such coverage appears mainly in office buildings, shopping malls in very complex environment. Although the three dimensional FDTD method has shown great promise, the calculation time is very environment dependent and exceeds the calculation time of ray tracing or ray launching in most cases. In this article, we focus on the theoretical estimation, comparison and combination of FDTD and ray methods in aspects of the algorithmic complexity. [7]

This article introduces the simulation and measurement indoor environment, and the FDTD and ray methods. Especially important will be our results for determine the size of FDTD simulation volume in case of combined ray and FDTD method [1], [2], which become highly important for indoor simulation of MIMO radio channel.

II. FDTD METHOD

The FDTD method is a time domain solution of the Maxwell's equations described in differential form and is widely used in circuit analysis because of its simplicity. The method divide the space investigated into finite grid elements and on the grid the time and space approximation of the electrical and magnetic field strength is performed. [3]

There exist many various forms of the FDTD in one, two or three dimensions and for many coordinate systems or grids and material types. For the indoor wireless channel simulation the two or three dimensional rectangular coordinate system are mainly chosen with linear lossy dielectric materials in volumes.

Lajos Nagy is with the Department of Broadband Infocommunications and Electromagnetic Theory, BME – Budapest University of Technology and Economics Goldmann György tér 3, Budapest, H-1111, Hungary, e-mail: nagy@mht.bme.hu

Starting from the generalized differential matrix operators, the Maxwell's curl equations can be express in the rectangular coordinate system, next the Yee algorithm [4] is than used for a discrete grid and consider a substitution of central differences for the time ($\partial/\partial t$) and space ($\partial/\partial x$, $\partial/\partial y$, $\partial/\partial z$) derivatives one get for the time marching solution of the coupled equations. The algorithm defines the discretized field components in the FDTD rectangular unit cell (the Yee cell). This cell in three dimension has volume of $\Delta x \Delta y \Delta z$ and the electric and magnetic field components locations are interleaved by half of the discretization length ($\Delta x/2$, $\Delta y/2$ and $\Delta z/2$).

The discretization on the simulation volume is made by cubic lattice so $\Delta x = \Delta y = \Delta z = \Delta$ which results in a significant simplification of the finite difference equations. Stability of the FDTD solution requires that the electromagnetic wave must not pass through more than one cell in one time step, i.e. the time step and the unit cell dimension satisfy the Courant condition.

III. SIMULATION AND MEASUREMENT IN INDOOR SCENARIO

In building propagation measurements, in the frequency band of 433 MHz are presented for narrow band applications, short range devices especially active and passive Radio Frequency Identification (RFID). The propagation model based on 3D FDTD (Finite Difference Time Domain) simulation is proposed and the simulated results are compared with measured ones.

The radio propagation measurements are realized at the 6th floor of a typical office building which has 7 floors, made partially from concrete and brick. (Fig. 1.)



Fig. 1. Indoor measurement scenario

The model database contains 12 types of material and wall thickness combinations which are marked as different colors on Fig. 2.

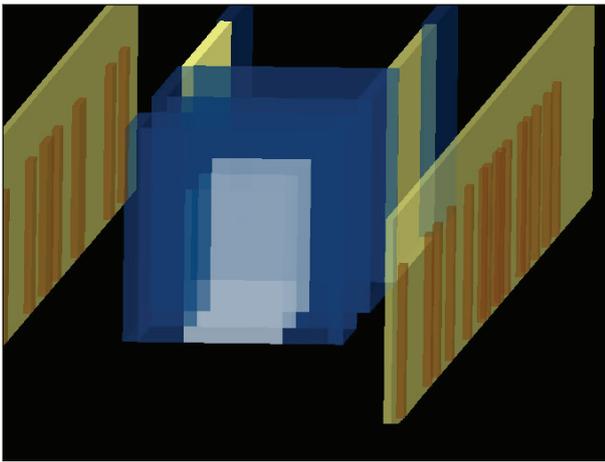


Fig. 2. Indoor 3D model (different materials different colors)

The simulation area can be seen on Fig. 3. is only a part of the total area of the floor but this limitation was necessary to keep the memory and calculation time requirement of 3D FDTD method as acceptable.

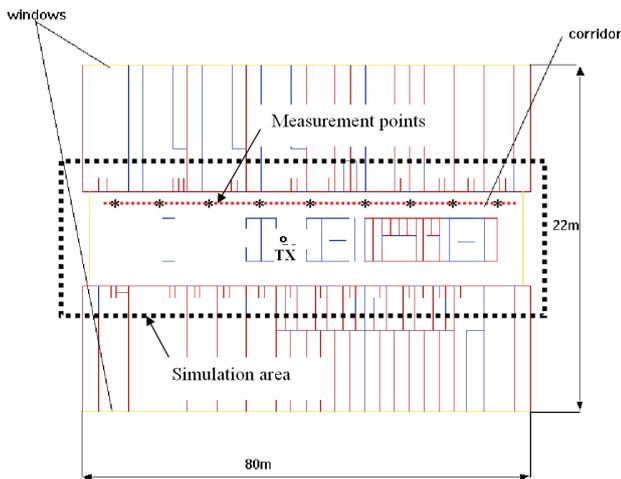


Fig. 3. Indoor measurement scenario floor plan with simulation area

The simulation volume for FDTD has $90 \times 11 \times 3$ cubic meter size, and $\lambda/20 \approx 30\text{mm}$ resolution of the FDTD results 120 mill. of cells.

The main drawbacks of the FDTD methods can be seen on Fig. 4 and 5. It is necessary to fulfill the time and space sampling conditions and this conditions result extreme memory and calculations time requirements.

The narrowband path loss measurements were performed using two quarter wavelength dipoles, which were manufactured and characterised for the channel measurements. Spectrum analyser was used for the received power and the channel attenuation measurements.

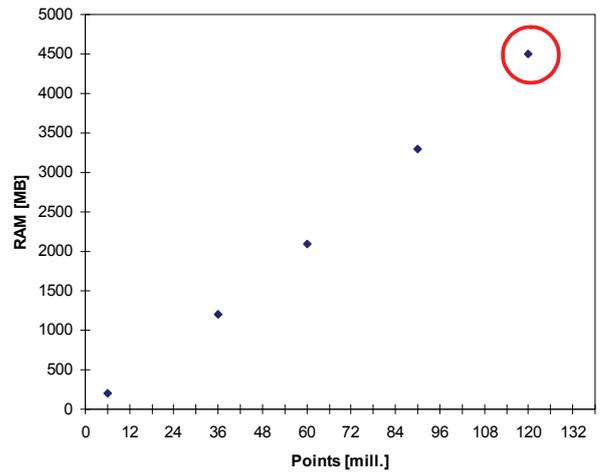


Fig. 4. Memory requirement of the simulation

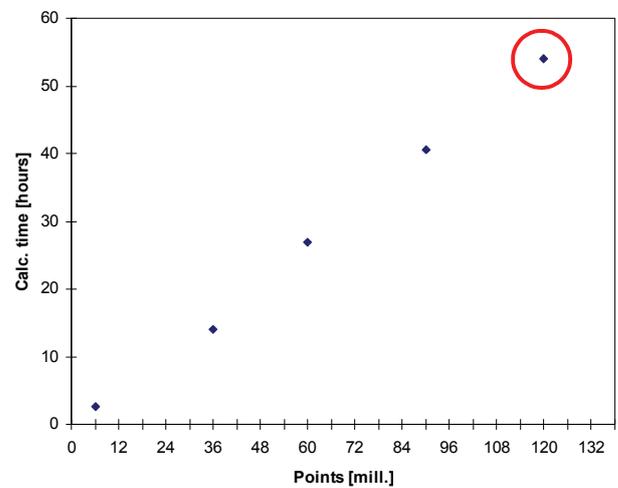


Fig.5. Calculation time requirement of the simulation

The dipole antennas are quarter wavelength dipoles balanced with sleeve balun, which is constructed in form of split coax balun.

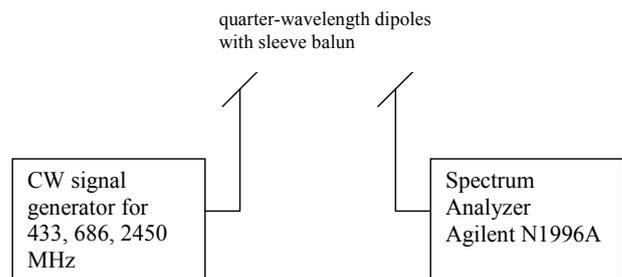


Fig.6. Measurement setup

The Fig. 7. shows the comparison of the FDTD simulation and measurement results. The average error: -1.74 dB and the error standard deviation: 15.5 dB between simulation and measurements.

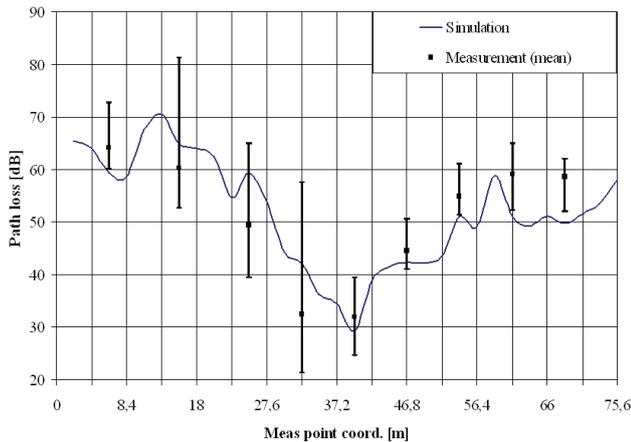


Fig. 7. Path loss comparison of simulation and measurements

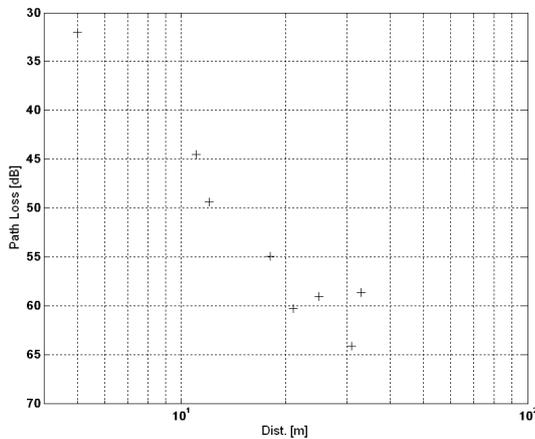


Fig. 8. Distance dependence of path loss (measured mean values)

8. which is in good agreement in typical indoor propagation scenario.

The 3D FDTD simulation results on Fig. 7 show good agreement to the measurement ones but as it was shown on Fig. 4 and 5 the tremendous calculation time and memory requirement make not possible to use the method in everyday engineering modelling practice.

Therefore the part VI suggests and investigate the possibility of usage of hybrid ray optical and FDTD method and investigate the optimal combination of the two methods.

IV. RAY METHODS

Ray methods are based on geometrical optics (GO) where the objects have dimensions that are much larger than the wave length and where electromagnetic waves are modelled as rays with flat wavefronts. In case of ray launching rays are followed until they hit an object, where a reflected/transmitted ray is initiated in the next reflection/transmission depth. The direction of the new ray after reflection/transmission is determined by Snellius' law.

A. Ray tracing

Ray tracing can be distinguished in ray launching and ray imaging techniques. Applying the imaging method, where new image sources are constructed of all existing (image) sources in the current reflection/transmission depth for all planes, each ray (path) from the transmitter to the receiver is exactly determined. The main problem of this scheme is, that complex scenarios with large number of walls become intractable in an affordable time because with an increasing number of interactions (reflection/transmission and diffraction) the computational effort exponentially increases.

B. Ray launching

Rays are homogeneously emitted from a unit sphere centered on the transmitter location and all regions are covered evenly by rays. Rays that intersect a detection area (reception sphere) around the receiver after a number of reflections, transmissions, and diffractions will account to the received signal. The computational effort linearly increases with the number of reflections and transmissions and therefore, ray launching is the preferred technique for large scenarios.

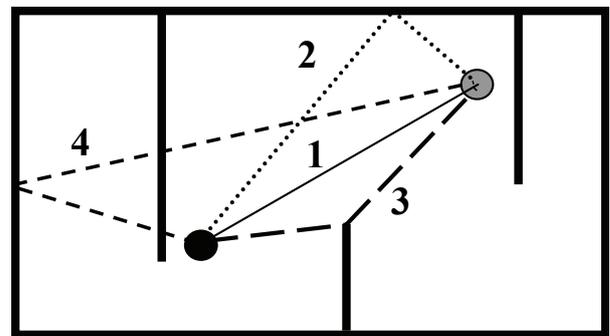


Fig. 9. Ray paths (1 - direct, 2 - reflected, 3 - diffracted, 4 – transmitted, reflected, transmitted) in indoor environment

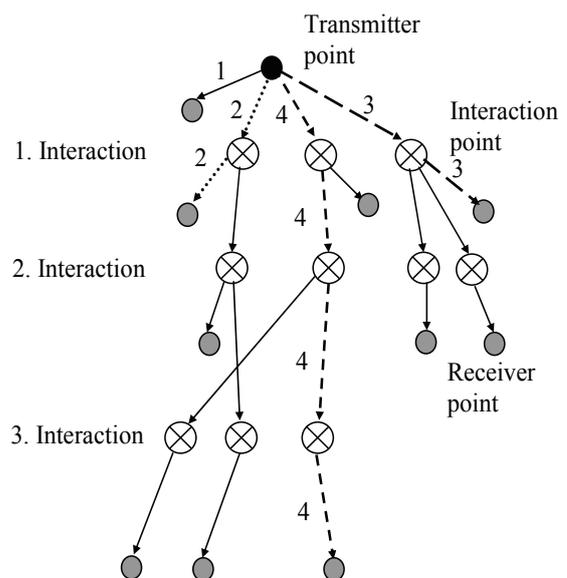


Fig. 10. Ray paths on a tree structure (Few paths from Fig. 9.)

V. ALGORITHMIC COMPLEXITY OF THE METHODS

The chapter introduces the estimation for algorithmic complexity of FDTD and Ray launching for 2D propagation calculations.

C. FDTD method - Computation time

We estimate the computational efficiency of the 2D FDTD method, which will be compared with ray methods in evaluating field strength prediction for indoor wave propagation modelling.

In order to make the comparisons we use uniform rectangular two dimensional grid of size $N_x=N_y=N_{FDTD}+2N_{PML}$ (where N_{PML} is the thickness grid size of the absorbing boundary layer PML – Perfectly Matched Layer).

For the 2D FDTD method the total number of numerical operations can be expressed as

$$\begin{aligned} F_{FDTD} &= F_{steady} \cdot F_{iter} = \\ &= 2\sqrt{2}N_{FDTD} \sqrt{\frac{\epsilon_{obj}}{\epsilon_0}} 28(N_{FDTD} + 2N_{PML})^2 \approx \\ &\approx \sqrt{\frac{\epsilon_{obj}}{\epsilon_0}} N_{FDTD} (N_{FDTD} + 2N_{PML})^2 \end{aligned} \quad (1)$$

where F_{steady} is the number of iteration steps to reach steady state, can be estimated by taking into account the wave speed in the inhomogeneous structure. F_{iter} is the number of numerical operations in a single iteration and can be estimated by counting the algebraic operations.

For simple estimation the total number of numerical operations in (1) the $\epsilon_{obj}/\epsilon_0 = \epsilon'_r < 10$ for the building materials.

D. Ray launching - Computation time

The Ray Launching method is not specific effective for the calculation of field strength in a specific point but for area coverage calculations has many advantages. By introducing the power threshold for finishing the trace of the ray launched, therefore no a priori knowledge on the importance of special ray contributions has to be included. Next, the behaviour in computation time depending on the number of interactions and the number of walls to consider is basically a linear one. Fig. 11 shows the results in relative computational time obtained in the given test area when increasing the maximum number of interactions but containing the number of subsequent diffraction processes to one. Time is given relative to the calculation with one interaction only.

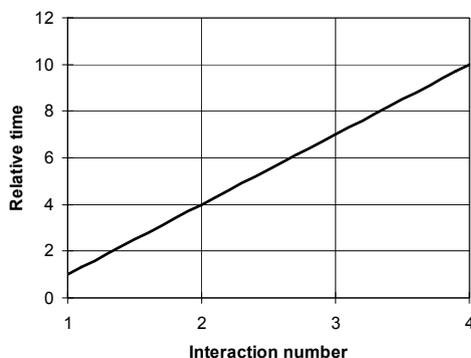


Fig. 11. Relative computational time of RL method

The ray launched has to trace on the area investigated for a maximum distance

$$l_{max} \approx (2i+1)N\sqrt{2} \quad (2)$$

where i is the number of interactions, N is the discretization step and detection circle radius.

The ray tube angle for ray launching can be expressed by the detection circle radius and maximum tracing length as

$$\alpha \approx \frac{1/N}{l_{max}} = \frac{1}{(2i+1)N^2\sqrt{2}} \quad (3)$$

Therefore using the results in Fig. 11. and Eq. (3) the algorithmic complexity of Ray Launching method has the dependence of $F_{RL} \approx N^2 i (2i+1)$

For a single frequency area coverage calculation the Ray Launching has a calculation complexity dependence of $\sim N^2$ on problem size, however the FDTD complexity dependence of $\sim N^3$.

The multiple frequency analyse needs of course a more detailed investigation. First the time dependent exciting signal spectrum has to be determined and performing Ray Launching calculation for every frequency excitation. Therefore the complexity results will have a dependence on signal waveforms also.

VI. HYBRID RAY OPTICAL AND FDTD METHOD

The hybrid Ray Optical and FDTD method will be illustrated for a two dimensional indoor scenario can be seen on Fig. 12. There is a rectangular room with two irregularities (columns) inside.

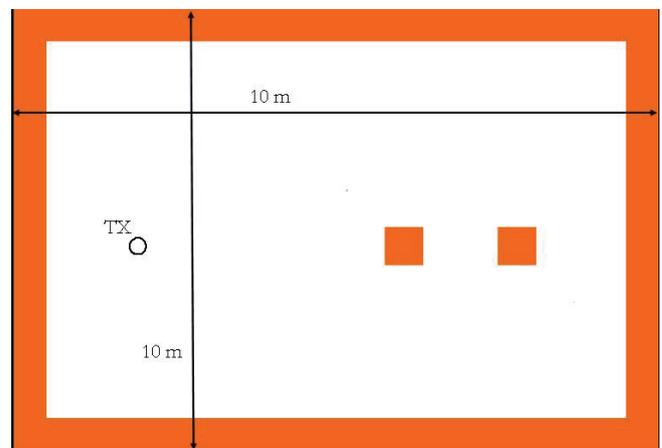


Fig. 12. Investigated indoor environment

Fig. 13-14 show field distribution simulated for the indoor scenario using Ray Optical Method (Fig. 13) and FDTD (Fig. 14) The Ray Optical simulation takes only account the reflections from main walls and not the effects of columns.

It is obvious that the field outside the irregular region is not differ at the two cases therefore the outer problem can be solved using Ray Optical Method e.g. Ray Launching and the FDTD is used for the inner problem for irregular region.

The Fig. 15 shows the difference field of Ray Optical and FDTD respectively. It can be unambiguously identify the irregularity region causing a notable difference between the two models.

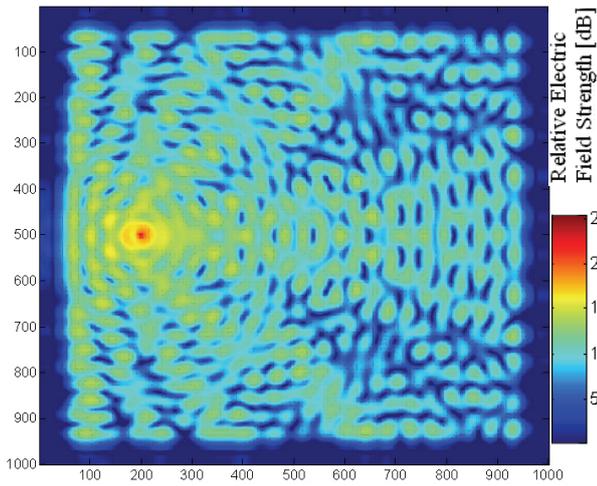


Fig. 13. Field distribution (Ray Optical model), reflection from walls up to maximum 5 rays

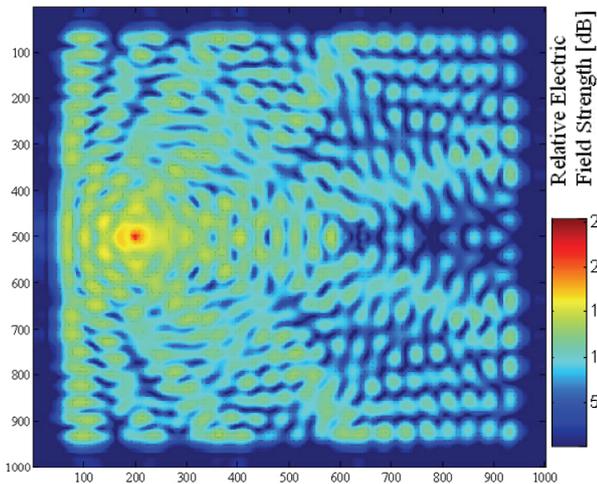


Fig. 14. Field distribution (FDTD model)

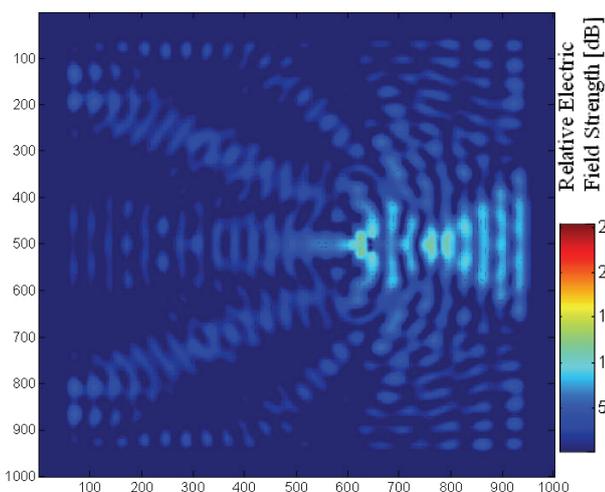


Fig. 15. Difference field distribution (Ray Optical and FDTD model field strength difference)

With the illustration above the Hybrid Ray Optical and FDTD method can be formulated as an outer and inner problem with common boundaries. The Fig. 16 shows this concept demonstrating with one ray from transmitter achieving the boundary of the inner FDTD region and using as excitation field on the boundary.

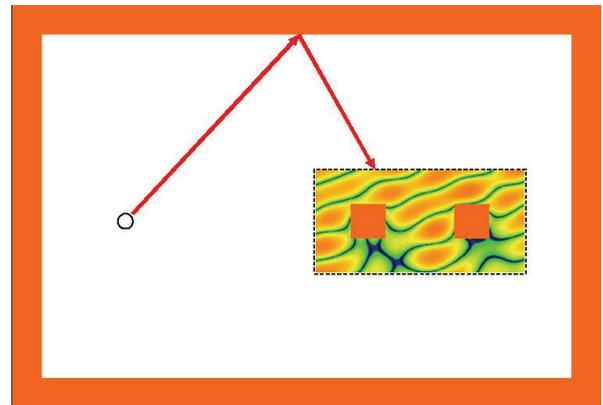


Fig. 16. Hybrid Ray Optical and FDTD model concept

The Ray Optical model launches rays uniformly from transmitter antenna and after simulating the physical propagation effects as direct, reflected, transmitted, diffracted waves calculates the incidence fields for excitation of the FDTD model. The Fig. 17 shows the launched cases as

- direct wave,
- direct + one reflected wave behind the FDTD region,
- direct + two reflected waves behind and advance the FDTD region,
- direct + four reflected waves behind, advance and sides the FDTD region,

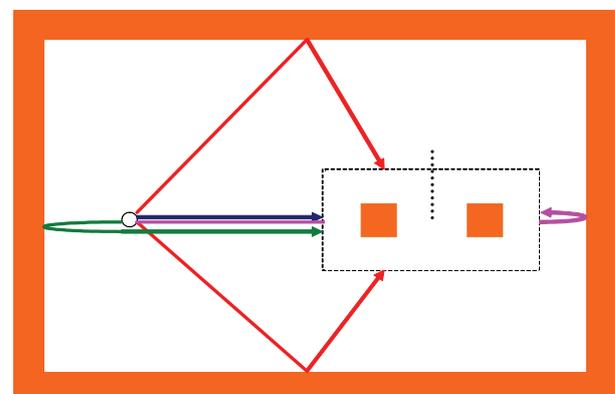


Fig. 17. Hybrid Ray Optical and FDTD model incidence waves

Comparison of Hybrid and FDTD methods will be introduced on Fig. 18. The path loss results on the dotted line points (Fig. 17) are showed. In the shadow region between the two columns the path loss difference is notable if only the rays from front and back walls are taken into account at the ray launching calculation. Therefore the ray launching model has to be prepared carefully for the outer problem solving to avoid such errors because the FDTD inner problem solver is not able to compensate that. Outside of shadow region the agreement is quite good and illustrates that such geometrical locations can be characterized by less dominant incident rays.

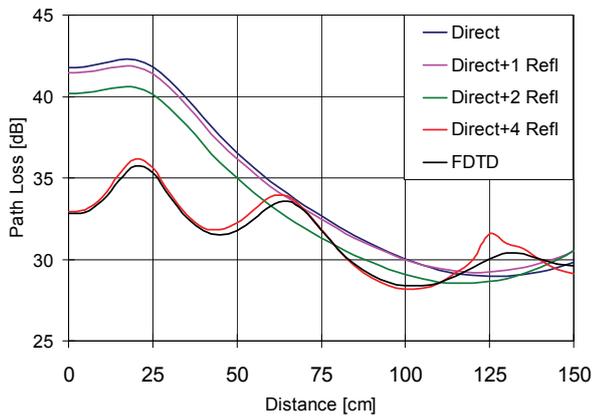


Fig. 18. Hybrid and FDTD model comparison. Distance measured from midpoint of the geometry on Fig. 17.

VII. OPTIMAL SIZE OF FDTD AREA

The cardinal question of the hybrid simulation model formulation is the size of the FDTD region. This part shortly summarizes the effect of the FDTD region size.

The same geometry as on Fig. 12 has been analyzed using different FDTD region sizes and direct + four reflected waves solving the outer problem.

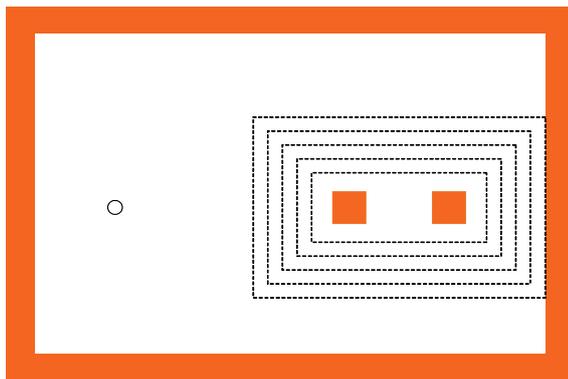


Fig. 19. Hybrid model FDTD regions

RMS error is compared for the five FDTD region sizes on Fig. 20. The error dependence is ambiguous there is no clear indication on the proper FDTD region size. The area indicated by number 2 has almost the minimum error but with increasing the area the simulation error not decreasing. The last case indicated by number 5 also partly contains the back wall.

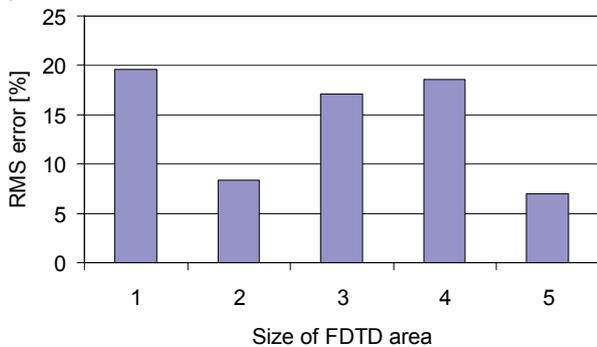


Fig. 20. RMS error of Hybrid method for different inner problem sizes. The numbers are indicating the increasing size of area

Because there is no unambiguous indications on requirement increasing the FDTD inner problem simulation area, therefore the algorithmic complexity optimum point can be also used as the indicator of simulation area.

The next calculations are using the same resolution for outer Ray Launching and inner FDTD solvers. The concept is illustrated on Fig. 21 showing rays followed and used as excitation as dense as the FDTD inner problem grid.

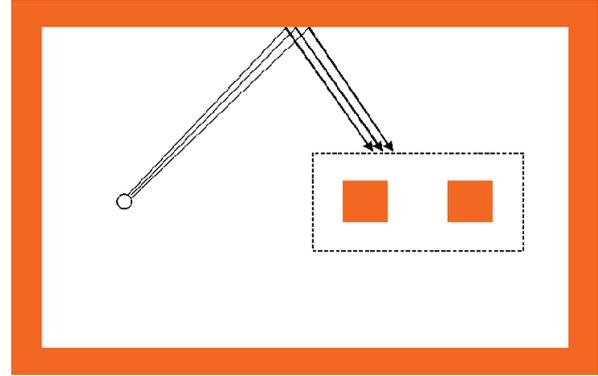


Fig. 21. Ray Optical method with the same density as FDTD grid

The optimum FDTD region area can be calculated as follows. First we express the calculation complexity of the hybrid problem

$$T_{Sum} = k_{RL} (N_{RL}^2 - N_{FDTD}^2) + k_{FDTD} N_{FDTD}^3 \quad (4)$$

$$N_{FDTD} = \eta \cdot N_{RL}$$

where

k_{RL} is the complexity factor of Ray Launching

k_{FDTD} is the complexity factor of FDTD

T_{sum} is the hybrid problem complexity

Next we calculate the optimum Ray Launching area size as a portion of the total problem size

$$\frac{d}{d\eta} T_{Sum} \Rightarrow \eta_{opt} = \frac{2k_{RL}}{3k_{FDTD}} \frac{1}{N_{RL}} \quad (5)$$

Therefore the FDTD area size optimum depends on the complexity factors of the Ray Launching and FDTD methods and on the total grid size of the problem N_{RL} .

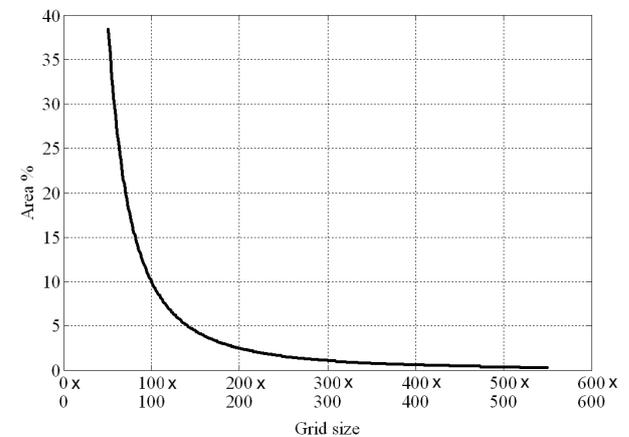


Fig. 22. Optimum area size portion of FDTD for Hybrid method

VIII. CONCLUSIONS

The radio propagation measurements are published with FDTD simulations at typical office building made partially from concrete and brick. Path loss dependence on distance and distribution was determined for small distance cases which results can be used for short distance radio developments in UHF band. In spite of good agreement of introduced FDTD simulation results we focus on investigation and possible application of hybrid ray tracing and FDTD method to reduce the simulation time and memory requirement.

The analytic investigation of algorithmic complexity of the method underlies the detailed investigation of hybrid ray tracing and FDTD method which can be very important for later simulations for MIMO indoor wave propagation calculations.

The optimal FDTD area calculation supports the usage of hybrid method and gives a good approximation for choosing the simulation area.

The article mainly focus on 2D FDTD and hybrid methods for analytic investigations but the procedure can be extend for 3D simulation environment.

REFERENCES

- [1] Ying Wang; Safavi-Naeini, S.; Chaudhuri, S.K., *A hybrid technique based on combining ray tracing and FDTD methods for site-specific modeling of indoor radio wave propagation*, Antennas and Propagation, IEEE Transactions on Volume 48, Issue 5, May 2000 Page(s):743 – 754
- [2] Wang, Y.; Safavi-Nacini, S.; Chaudhuri, S.K., *A combined ray tracing and FDTD method for modeling indoor radiowave propagation*, Antennas and Propagation Society International Symposium, 1998. IEEE Volume 3, Issue , 21-26 Jun 1998 Page(s):1668 - 1671 vol.3
- [3] Allen Taflove, Susan C. Hagness, *Computational Electrodynamics: The finite-difference time-domain method*, Artech House, Norwood, 2005
- [4] Yee, K. S., *Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equations in Isotropic Media*, IEEE Trans. Ant. Prop., 14(3), 302, 1966
- [5] Lajos Nagy, *MIMO cube in realistic indoor environment*, The European Conference on Antennas and Propagation, EuCAP 2006, 6-10 November 2006, Nice, France
- [6] B.E. Gschwendtner, G. Wölfle, B. Burk, F.M. Landstorfer, *Ray Tracing vs. Ray Launching in 3D Microcell Modelling*, Proc. EPMCC'95, Bologna, 1995, pp. 74–79
- [7] Lajos Nagy, Robert Dady, Andrea Farkasvolgyi, *Algorithmic complexity of FDTD and Ray Tracing method for indoor propagation modeling*, Antennas and Propagation, EuCAP 2009, 23-27 March 2009, Berlin, Germany