Abstract
An enhanced 3D Ray Tracing Propagation Algorithm for indoor EM Wave Propagation useful at various frequencies (e.g. UMTS, TETRA) is presented. By adopting reasonable simplifying assumptions, computation time is reduced of at least an order of magnitude, if compared to a brute force approach. In order to evaluate path losses, a classical recursive image method has been modified and 3D geometry was reduced to multiple 2D. By using the proposed approach, an higher number of reflections can be evaluated, thus increasing simulation accuracy.

INTRODUCTION
The analysis and simulation of electromagnetic (EM) wave propagation represent a crucial task in planning wireless networks for ICT application in complex indoor environments: for example, when emergency communication requirements must be fulfilled, an adequate planning is unavoidable in order to grant a service reliable both for quality and confidence. Deterministic wave propagation models are growing their importance day after day, becoming fundamental for the characterization of indoor propagation. Moreover an high simulation accuracy often requires a huge computation time that sorely tries CPU’s strength and speed. In most cases hardware empowering is not enough to reduce computer simulation time, which can vary from minutes to weeks. Therefore it is necessary to perform a deep optimization on the algorithm and simplifying assumptions on the propagation models are often unavoidable to increase performances. Ray tracing is a good deterministic approach when wavelength becomes nearly negligible if compared to obstacle dimensions and the total field can be evaluated as a sum of independent components propagated in different directions. Each component (ray) is roughly modified by the propagation media in terms of phase and amplitude (attenuation) following an exponential equation. The focal point of the method is to find “all” the possible paths from a source to a receiver and evaluate the attenuation by the path length of the ray. The weak point of this approach is the unavoidable CPU’s calculation time “explosion” with complex geometry. In this work, ray tracing approach is applied to indoor propagation where the complexity is reduced by simplifying assumptions.

BRUTE FORCE APPROACH ANALYSIS AND FURTHER OPTIMIZATION
An indoor environment is characterized by lots of geometric objects. It would be nearly
impossible to analyze the original environment, so a digital (quantized) representation is required. In other words objects belonging to the environment can be represented by faces. Smaller the faces, higher the resolution. Objects, imperfections and everything smaller than wavelength can be neglected with good approximation. Moreover, we suppose that the indoor environment is empty, furnitureless.

The first approach to the ray tracing method is to consider a receiver and a transmitter placed everywhere in the environment, as shown in Fig. 1, for the simple case of 2D environment, where TX is the transmitter and RX the receiver. Ray paths are traced considering the one in line of sight (LOS) and the others are obtained by wall reflections: a classical recursive image method can be used.

The total attenuation (path loss) of the EM field belonging to each ray is given by a component of path loss and a component of reflection loss, due to the not perfect reflecting wall.

The number of paths with one reflection is given by the number of walls (faces) \( N \) in the environment, because one image per face has to be computed (1st order images). With two reflections each image (associated to a face) calculated before is a new equivalent source that requires to be reflected on the other \( N-1 \) walls, generating 2nd order images. So, a path with \( K \) reflections requires to evaluate \( N(N-1)^{K-1} \) images.

The total field is given by the sum of the contribute of each ray; if we consider a max of reflection order equal to \( K \), the number of path evaluation (complexity) is:

\[
C = 1 + N \sum_{i=1}^{K} (N - 1)^{i-1}
\]

The relevant assumption we can made for an indoor environment is that floor and ceiling, in most cases, are parallel and walls are perpendicular to the floor. Considering a ray’s projection on the floor we individuate a family of rays which have the same vertical projection. Consequently we can split a path into two components: the horizontal one (or 2D) that represents the path projection on the floor, and the vertical one which represents reflections by floor and ceiling.

Thanks to the simple vertical geometry, computing the path length doesn’t require evaluation of images. Each reflection on the floor and ceiling consists of an angle of incidence equal to the reflection angle, so an equivalent ray can be built, as shown in Fig. 2. The height \( H_f \) is automatically given by a simple relation:

\[
H_f = H(n - 1) + (\text{mtx } htx + \text{mrz } hrx + \text{(mtx)} htx' + (\text{mrz}) hrx')
\]
where \( mtx \) and \( mrx \) are pseudo-boolean coefficients obtained by the following table:

<table>
<thead>
<tr>
<th>( D )</th>
<th>( S )</th>
<th>( mtx )</th>
<th>( mrx )</th>
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<tr>
<td>0</td>
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Table 1. \( mtx = \text{not}(S) \) \( mrx = D \text{ xor } S \)

\( D \) and \( S \) represent the case in which the number of reflections is even (\( D = 0 \)) or odd (\( D = 1 \)) and if the first reflection is on the floor (\( S = 0 \)) or on the ceiling (\( S = 1 \)). The value \( H_f \) is independent by the distance between transmitter and receiver, so it can be pre-calculated. Once the value of \( H_f \) is known, the total path length is immediately given by the Pitagora’s theorem. Consequently the total computation in order to find the path length in a simple vertical geometry consists of only one arithmetic calculation. The complexity of this algorithm is therefore 1. Tracing a 3D ray path with these equations, the algorithm is decomposed into two parts, vertical and horizontal (2D). If \( N \) represents the number of walls in the indoor environment, the effective number of walls to use with the 2D part of the algorithm is \( N-2 \), obtained removing ceiling and floor. Decomposing the total number of reflections \( K \) into two components, \( K_v \) and \( K_h \), respectively the number of vertical and horizontal reflections, the total complexity of the algorithm becomes:

\[
C_1 = 1 + (1 + K_v)(N - 2)\sum_{i=1}^{K} (N - 3)^{i-1}
\]  

(3)

The behavior of this function is shown in Fig. 3, where \( K_v \) has been varied to analyze the changes in the total amount of calculation complexity.

Computing the field in an entire environment requires to cover all the space with a
receiver grid. As example, a cubic room environment is used. Dividing the space into $m$ points per dimension, the resultant number of receivers is $m^3$. Consequently, the total number of calculations computed using the brute force approach is:

$$
C_T = m^3 \left( 1 + N \sum_{i=1}^{K} (N - 1)^{-i} \right) \equiv m^3 N \sum_{i=1}^{K} (N - 1)^{-i} \quad (4)
$$

The use of the optimized algorithm allows to use the 2D part of the path traced for all the $m$ receivers with the same projection on the floor.
In the optimized algorithm the total amount of calculations is:

$$
C_{T'} = m^2 \left( m + (1 + K_v) \sum_{i=1}^{K} (N - 3)^{-i} \right) \equiv m^2 (1 + K_v) (N - 2) \sum_{i=1}^{K} (N - 3)^{-i} \quad (5)
$$

CONCLUSIONS

An example of map covering is shown in Fig. 4: on a common PC, elaboration time of brute force algorithm was about 15 minutes. The new approach allows to obtain the same covering map in less then 1 minute.

REFERENCES