AN ADAPTIVE MULTI-RESOLUTION ALGORITHM FOR 2D SIMULATIONS OF INDOOR PROPAGATION

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INTRODUCTION
The increase of Indoor wireless networks applications calls for robust and efficient tools for predicting wave propagation in such complex environments.

The ParFlow approach has been proposed by Choppard et al. (1) in the context of GSM base station planning. This technique is a time-domain discrete approach which accurately reflects the behavior of wave propagation but in turn requires very high computation and time resources. Initially this method has been implemented in a parallel architecture to reduce the computation time. Recently JM Gorce and S Ubéda (2) have proposed a new resolution scheme (FDPF=Frequency Domain ParFlow) to solve the discrete ParFlow equations in the Fourier domain. The problem is thus written as a wide linear system. We have proposed in (2) to solve this system in two steps taking advantage of a multi-resolution approach.

The first step computes a cell-based tree structure referred to below as the pyramid. This step is considered as a pre-processing phase since this computation does not require the knowledge of a source location.

In the second phase a radiating source is simulated, taking advantage of the pre-processed pyramidal structure. The advantages of this approach are the following:
- The use of the pyramid allows to drastically reduce the CPU charge needs to compute the coverage of several sources.
- The multi-resolution is also used to assess the coverage prediction at a lower resolution than the simulation resolution.

In this paper, a new algorithm is proposed to define an environment-based adaptive pyramidal structure avoiding artefacts near walls and other discontinuities.

PARFLOW THEORY

The time domain ParFlow algorithm

The time domain ParFlow approach simulates the field radiated by a source located somewhere on a 2D regular discrete grid. In this method the electric field is settled in a 2D regular grid. In this method the electric field is settled in components, the flows (discrete ParFlow equations (1)). In this paper, these flows are referred to below as the pyramid. This step is considered as a pre-processing phase since this computation does not require the knowledge of a source location.

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PARFLOW THEORY

The time domain ParFlow algorithm

The time domain ParFlow approach simulates the field radiated by a source located somewhere on a 2D regular discrete grid. In this method the electric field is settled in 5 components, the flows (Figure 1), which are driven by local transition matrices derived from the Maxwell’s equations (1). In this paper, these flows are referred to as \( f_d \) and \( g_d \) respectively for incoming and outgoing flows, where the indice \( d \) (E,W,S,N) indicates the cardinal direction of the flow.

An intern flow \( f_{ij} \) is used to simulate non perfect dielectric media having a specific dielectric coefficient.

These virtual flows introduced at the microscopic level properly induce reflection and diffraction effects at a macroscopic level (see below, in the result section).

The ParFlow algorithm is derived from the work of P.O. Luthi (3) in which a formulation has been proposed for general wave propagation problems on a regular lattice. However, when applied to the electromagnetic wave propagation on a first order square lattice, the algorithm is strictly equivalent to the well-known transmission line matrix (TLM) earlier proposed by Hoefer(4); Johns (5) and others.

In this paper, the problem is restricted to 2D simulations both for clarity sake and computational efficiency. Therefore the transverse component of the E-field only is computed according to:

\[
\Psi_y = \left( f^{+}_y + f^0_y + f^{-}_y + Y_y f^{||}_y \right) / n_y (1)
\]

Choppard et al. (1) have proposed the use of a cellular automata to solve the problem, with the following propagation-scattering equations:

\[
g_y(t) = \sum_i f_y(t - dt)
\]

and

\[f_y(t) = N(g_y(t)) \]

where \( \Sigma_y \) is the scattering matrix of cell \((i,j)\) and:

\[
f_y = \left[ f^+_y, f^0_y, f^-_y, f^\parallel_y \right] ; g_y = \left[ g^E_y, g^W_y, g^S_y, g^N_y \right] \]

\( N(g_y) \) is the vector of neighbour outgoing flows:

\[
N(g_y) = \left[ g^E_{y+1}, g^W_{y-1}, g^S_{y+1}, g^N_{y-1} \right]
\]

The frequency domain parflow method (FDPF)

A global inspect of the system is meaningful to develop the frequency domain algorithm and further the multi-resolution approach.

Let the flows be gathered into a vector of unknowns as follows:

\[
F = \left[ f^T_{1,1}, f^T_{1,2}, \ldots, f^T_{1,N}, f^T_{2,1}, f^T_{2,2}, \ldots, f^T_{N,N} \right] \]

Figure 1: the incoming (a) and outgoing (b) flows associated with a cell of the regular mesh.
where \( T \) stands for transpose vector.

The ParFlow equation may then be written as:

\[
F(t) = \Sigma_i F(t - dt) + S(t) \tag{5}
\]

where \( \Sigma \) is the global scattering matrix and \( S(t) \) is the source vector, which is null everywhere except for the indices corresponding to the source position.

The frequency domain equation is obtained by the Fourier transform, leading to:

\[
(F - \Omega) \cdot \tilde{F}(\nu) = \tilde{R}(\nu) \tag{6}
\]

where \( \Omega = \Sigma \cdot e^{-j2\pi t} \)

At this point, it is assumed that the radiating source is narrow-banded, working at frequency \( \nu_0 \). It follows that further developments correspond to a steady-state study and propagation time delays as well as time spreading won’t be assessed. This method therefore cannot apply for time spread channel simulations. In the context of WLAN planning tools, a mean received power estimation is assumed to be enough.

The linear system of Eq.(6) cannot be solved directly due to its large size. It is preferable to expend Eq. (6) as a geometric series:

\[
\tilde{F}(\nu) = \sum_{i=0}^{\infty} \Omega^i \cdot \tilde{R}(\nu) \tag{7}
\]

Note that in the frequency domain, the inner flow \( F_0 \) are not anymore necessary. The refraction index property may be introduced directly in the scattering matrix with 4 flows by weighting properly the matrix coefficients (see (2) for details).

The frequency domain algorithm

Solving equation (8) may be implemented through a cellular automata as well as the time domain approach, according to the following algorithm:

**Initialisation**:

\[
\tilde{F}^{(0)}_{ij}(t) = \tilde{f}^{(0)}_{ij}(t) = \tilde{g}^{(0)}_{ij}(t) \quad \text{(in source locations)}
\]

**Iterative Propagation**:

- \( \tilde{g}^{(i)}_{ij}(t) = \Omega_{ij} \cdot \tilde{h}^{(i-1)}_{ij}(t) \quad \text{(scattering)} \)

- \( \tilde{h}^{(i)}_{ij}(t) = N \tilde{g}^{(i)}_{ij}(t) \quad \text{(diffusion)} \)

- \( \tilde{f}^{(i)}_{ij}(t) = \tilde{f}^{(i-1)}_{ij}(t) + \tilde{h}^{(i)}_{ij}(t) \quad \text{(accumulation)} \)

Until convergence.

**A NEW MULTI-RESOLUTION APPROACH**

**The bloc level modelling**

The bloc concept is the first step toward the multi-resolution approach. As illustrated in Figure 2, let the pixels be gathered into regular blocks of size N x N. In each block, inner flows may be considered as intermediate variables in the calculus of flow exchange between blocs. It is therefore possible to solve the propagation problem by using the flows located on bounds only (see (2) for more details).

On each bloc bound, two flow vectors of size N are defined and represent the incoming and outgoing flows referred to as \( F_{ij} \) and \( G_{ij} \); \( d \in \{E,W,S,N\} \). A propagation matrix is associated with each bloc, and acts like the scattering matrix defined in the previous section but on flow vectors of size N per bound.

The scattering matrix structure is:

\[
\Omega_{ij} = \begin{bmatrix}
\Omega_{EE} & \Omega_{EW} & \Omega_{ES} & \Omega_{EN} \\
\Omega_{WE} & \Omega_{WW} & \Omega_{WS} & \Omega_{WN} \\
\Omega_{SE} & \Omega_{SW} & \Omega_{SS} & \Omega_{SN} \\
\Omega_{NE} & \Omega_{NW} & \Omega_{NS} & \Omega_{NN}
\end{bmatrix} \tag{8}
\]

where \( k,l \) are the indices of the bloc and the sub-matrix \( \Omega^{id} \) equates the propagation from \( F_{ij} \) to \( G_{ij} \).

The frequency domain algorithm may be then used but with vector incoming and outgoing flows instead of scalar ones.

At this point, it should be emphasized that this approach is more efficient than the pixel level algorithm. Indeed, the computation complexity of one iteration is similar in both cases but now the propagation is performed in one iteration directly over a bloc instead of a cell, with a processing gain about a factor of N.

**Building a pyramid**

The aim of the multi-resolution approach is to link...
several bloc levels in order to compute efficiently the propagation over the 2D environment.

Given two adjacent blocs A and B, having their own scattering matrix $\Omega_A$ and $\Omega_B$, a new bloc C is built by gathering these blocs as illustrated in Figure 3. In (2), we have shown that $\Omega_C$ may be computed from $\Omega_A$ and $\Omega_B$. For instance, when the blocs are gathered horizontally according to Figure 3, $\Omega_C$ is given by:

$$\Omega_C = P_1 \cdot P_2 \cdot P_1$$

(9)

where matrices $P_1$, $P_2$ and $P_3$ equate respectively the propagation from incoming flows to inner flows, between inner flows inside C and from inner to outgoing flows. They are given by:

$$P_1 = \begin{bmatrix} [0] & \Omega_{EW} & \Omega_{NS} & [0] & \Omega_{NY} & [0] \\ \Omega_{SW} & [0] & [0] & \Omega_{BY} & [0] & \Omega_{NY} \end{bmatrix}$$

$$P_2 = \begin{bmatrix} I_d & -\Omega_{EW}^{-1} \\ -\Omega_{SW} & I_d \end{bmatrix}$$

It appears clearly that the main computation charge is due to the calculus of the matrix $P_2$, which requires a matrix inversion.

In order to propagate the flows of a source located either in A or B, it is necessary to compute the resulting source C. This task illustrated in Figure 3a, aims to propagate the west source vector of bloc A toward outgoing flows. The flows of the source C, $S(C)$, are given by:

$$S_C = [S_A^E, S_B^W, [S_A^S, S_B^S], [S_A^N, S_B^N]]$$

(10)

where $U_C = P_3 \cdot P_2 \cdot P_1$ is the up-link matrix of bloc C.

An adaptive pyramidal structure

It should be possible to build a regular pyramid for which blocs are gathered two by two alternately in x and y directions. However an approach which privileges homogeneous rectangular blocs is preferred for two reasons:

- The first concerns memory consumption and computation complexity. Homogeneous blocs may be reused several times, thus minimising the requested memory and the pre-processing computation charge.
- The second concerns the planing phase as described by Runser et al. (ref) in a joined paper. In order to plane antennas positions, it is not necessary to estimate the field at the ground level of the pyramid. A mean estimation over blocs is sufficient if blocs are homogeneous to avoid artefacts near discontinuities.

As a consequence, a descending algorithm has been chosen, starting at the top of the pyramid. A bloc is split into two sub-blocs, maximising a criteria which makes a trade-off between regularity (two sub-blocs of same size) and specificity (try to settle the bloc where the number of discontinuities is the higher). A bloc is always split in its larger dimension. In the case of an horizontal split, the vertical splitting line is chosen such as in this line the number of discontinuities is higher:

The splitting criteria is the following:

$$Q(j) = \sum_{i=1}^{N} D_j^N(i) / N$$

Figure 4 : the multi-resolution structure creates links between cells and higher level blocs until a unique bloc is achieved

**IMPLEMENTATION**

The propagation simulation is done in three steps. The two first steps don’t take care the source location. They thus may be considered as pre-processing.

**Pre-processing**

**Pyramid achievement** - Firstly, the pyramid structure is computed according to the criteria defined in previous section. A data base is built containing the bloc references and their mutual up and down-links. For each bloc size, several blocs may be defined according to their physical content (air, brick, ...). Thus, the data base has 3 dimensions, width, height and type of blocs. A bloc may be completely described by pointers on its bloc sons.

**Propagation matrix evaluation** - For each bloc type, starting from the ground level, up-link and down-link matrices are computed. This stage corresponds to the heavier CPU charge of the method.

**Source radiation simulation**

It is therefore possible to compute a source contribution, as well for coverage predictions or simply for a specific radio link between two points. The coverage calculation
may be performed at a strategic level in the pyramid. Indeed, the pixel resolution is not significant for planing problems. It is therefore possible to stop the calculus when a predefined bloc size is reached. Taking advantage of the adaptive pyramidal structure it is furthermore possible to warrant that these blocs are homogeneous. Then, the a mean power of incoming flows is a good estimator of the mean electric field power over this bloc.

SIMULATION RESULTS

The results obtained for a 2D environment corresponding to our lab are presented. The environment size corresponds to a rectangular area of 20mx73m, which has been bordered in the simulation by specific cells (absorbing medium) in order to avoid boundaries artefacts. The simulation frequency is not equal to the experimental frequency. Indeed, the resolution required in TLM like problems is approximately 8 times lower than the wave length. For wLAN, at 2.4GHz, this would impose a resolution lower than 2cm. As proposed in (1) we rather use an intermediate frequency, chosen such as the wavelength remains lower than the size of free-space blocs in the considered environments. As a consequence, the first input is rather the resolution expected for the coverage prediction. The fine resolution has been chosen to 10cm, which implies an intermediate frequency not higher than 500MHz.

The method has been implemented on a JAVA platform, running on a Pentium bi-processor 800MHz with 1,24GHz of RAM.

In this simulation, the pre-processing phase requires about 10 minutes. The coverage prediction time is in the order of 1second to propagate a source to the top of the pyramid. Then, the coverage is predicted with less than 2 seconds to reach the homogeneous bloc level, about 20 seconds to reach the 10x10 bloc level and about 80s to reach the ground of the pyramid leading to the finest estimation.

DISCUSSION

In this paper a multi-resolution FDPF approach has been proposed. More precisely, a new non regular pyramidal structure which fits the particular arrangement of the Indoor environment has been presented. The use of a full-space discrete simulator instead of classical ray-tracing techniques is a challenge due to the inherent high computation requests. However, we demonstrate that the use of a multi-resolution approach allows to perform some calculus in a pre-processing phase, independently of source locations.

When these calculus have been down, it is possible to test a source with a reasonable CPU charge, by using the pyramidal structure and by limiting the accuracy level of the results. The use of this algorithm in the context of WLAN planing is presented in an accompanying paper (6).

Future improvements will be down in terms of calculus efficiency in two ways:

Firstly, the time consuming actually obtained in our implementation has been shown to be in a large part due to memory access to the data base and bloc matrices.

Secondly, when the blocs are large, the up and down-link matrices are sparse and moreover some very low coefficients could be eliminated. An eigen-values decomposition could reduce drastically the memory and computation requests.

REFERENCES :


