

# FDTD COMPUTATION FOR LARGE-SCALED NUMERICAL DOSIMETRY ON PARALLEL PERSONAL COMPUTERS

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## 1. Introduction

Since it is very difficult to quantify microwave absorption directly in a living human, dosimetry is forced to rely mainly on computer simulation with high-resolution numerical human models obtained from magnetic-resonance imaging (MRI) or computed tomography (CT) scans. The Finite-Difference Time-Domain (FDTD) method [1] is currently the most widely accepted means for the numerical dosimetry. By discretizing space into a number of cells, and by assigning each cell the corresponding permittivity and conductivity, this method offers great flexibility in modeling the heterogeneous structures of anatomical tissues and organs. However, The use of millimeter high-resolution human models becomes difficult as a huge amount of memory for computer simulation prohibits their use.

In this paper, a parallel FDTD computation system is developed using Linux-based personal computers. The parallelism is based on the Message Passing Interface (MPI) library [2]. Its performance is tested and an application to examine the whole-body effect on the user head dosimetry for a mobile phone is shown.

## 2. Parallelism with MPI Library

The FDTD formulations are derived from Maxwell's time-domain equations by applying central differences to time and space derivatives, as shown in the following equations:

$$E_z^{n+1}(i, j, k) = \frac{1 - \frac{\sigma \Delta t}{2\varepsilon}}{1 + \frac{\sigma \Delta t}{2\varepsilon}} E_z^n(i, j, k) + \frac{\Delta t}{1 + \frac{\sigma \Delta t}{2\varepsilon}} \left[ \frac{H_y^{n+1/2}(i, j, k) - H_y^{n+1/2}(i-1, j, k)}{\Delta x} - \frac{H_x^{n+1/2}(i, j, k) - H_x^{n+1/2}(i, j-1, k)}{\Delta y} \right]$$

$$H_z^{n+1/2}(i, j, k) = H_z^{n-1/2}(i, j, k) + \frac{\Delta t}{\mu} \left[ \frac{E_y^n(i+1, j, k) - E_y^n(i, j, k)}{\Delta x} - \frac{E_x^n(i, j+1, k) - E_x^n(i, j, k)}{\Delta y} \right]$$

where  $\sigma$  is the conductivity,  $\varepsilon$  is the permittivity,  $\Delta x$ ,  $\Delta y$ ,  $\Delta z$  are the cell sizes, and  $\Delta t$  is the time step. To compute the electric field  $E$  at  $(i, j, k)$ , we need its neighboring magnetic fields, and similarly, to compute the magnetic field  $H$  at  $(i, j, k)$ , we need its neighboring electric fields. If we divide the whole FDTD computation space into many subspaces, we only require exchange the electric and magnetic field data at the subspace boundaries. The FDTD method is therefore very appropriate to the parallel computation [3][4].

Referring to the division method of subspaces in [3], we divided the whole FDTD space into eight subspaces as shown in Fig.1. Each subspace is handled by a CPU, and all the CPUs execute the same program. To compute the field in the boundary cells, we need to know the field in the cells belonging to the neighboring subspaces. This was realized by using the MPI library to transfer the data from one CPU to another CPU. For simplicity, let us consider a one-dimensional case as shown in Fig.2. We divide the whole FDTD space into two subspaces:  $S_0$  and  $S_1$  in this case.  $S_0$  and  $S_1$  are handled by CPU<sub>0</sub> and CPU<sub>1</sub>, respectively. In the E-field computation, we pass  $H_1$  in subspace  $S_0$  to  $S_1$ , which

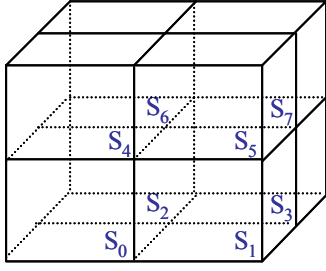


Fig.1 Dividing the FDTD space into 8 subspaces. Each subspace is handled by one CPU.

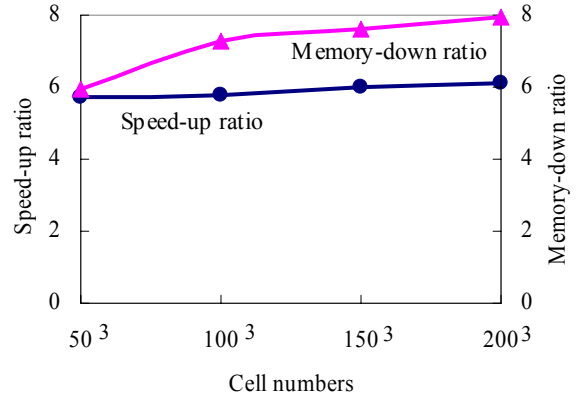


Fig. 3 Performance of the parallel FDTD computation system.

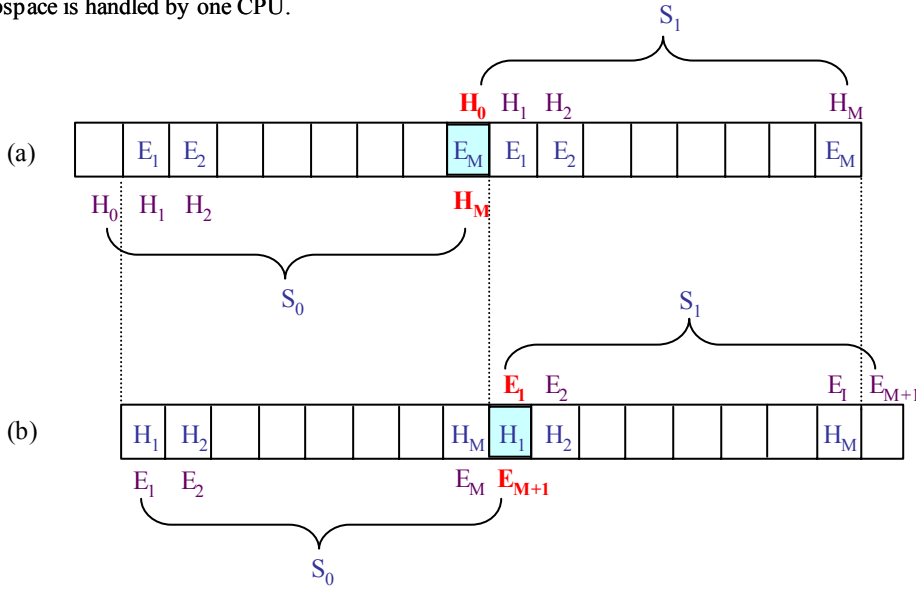


Fig.2 Data communication in the boundary of subspaces with MPI. According to the FDTD algorithm, to obtain  $E_{m+1}$   $H_{m-1}$  is needed, to obtain  $H_m$   $E_{m+1}$  is needed. Therefore, (a) Pass  $H_M$  in  $S_0$  to  $H_0$  in  $S_1$  for computing  $E_1$  in  $S_1$ . (b) Pass  $E_1$  in  $S_1$  to  $E_{M+1}$  in  $S_0$  for computing  $H_M$  in  $S_0$ .

is used as  $H_0$  for obtaining  $E_1$  in  $S_1$ . In the H-field computation, we pass  $E_1$  in subspace  $S_1$  to  $S_0$ , which is used as  $E_{M+1}$  for obtaining  $H_M$  in subspace  $S_0$ . It is straightforward to extend this algorithm to a three-dimensional case. In such a way we developed a parallel FDTD code for a parallel computation system. The parallel system consists of four personal computers (Dell PowerEdge 2550, Pentium III 1.26GHz), each of that has a dual-CPU and 4GB memory, which results in a parallel system having eight CPUs and 16GB memory in total. Data transfer among the computers is conducted through Gigabit network interface. The parallel FDTD code, which was written in Fortran 90, can run in a Linux operation system (OS) environment. Berenger's perfectly reflected layer (PML) boundary conditions were incorporated in the parallel FDTD code.

### 3. Performance Evaluation

Fig.3 shows a performance evaluation for our parallel system. Since we developed specially our parallel FDTD code for eight CPUs, we show only the results in the eight-CPU case. In Fig.3, the abscissa indicates the cell number of whole FDTD space, and the left and right ordinates indicate the speed-up ratio and memory-down ratio, respectively. The speed-up ratio was defined as the ratio of the run-time in one CPU case and that in eight CPU case, and the memory-down ratio was defined as the ratio of the memory required in each CPU when the computation is conducted in one CPU to that in

eight CPUs. For both the speed-up ratio and the memory-down ratio, the ideal value is eight because eight CPUs are used. From Fig.3 we found an almost fixed speed-up ratio of six that was close to the ideal value of eight. With enlarging the computation space, a further improvement may be expected. We also found a significant reduction of the memory required in each CPU with enlarging the computation space. For an FDTD computation space of 200 x 200 x 200 cells, we found a memory-down ratio of eight approximately, which means that the overhead for memory in the parallel code is almost negligible.

#### 4. Application

With the parallel FDTD system, we here show an application for large-scaled dosimetry of mobile phones. In the dosimetry evaluation of mobile phones, an isolated head model is generally used to obtain the one-gram or ten-gram averaged spatial peak specific absorption rate (SAR). Iskander et al. recently reported that the human body could affect the SAR in the head [5]. Neglecting the effect of the human body may result in an SAR underestimate. However, their body model was a highly simplified one, and had an unnatural shape especially for the shoulder. Using our parallel computation system, it becomes possible to conduct a large-scaled and high-precision analysis for the body effect. We employed an anatomically based whole-body human model whose original scan is known as the "Visible Man". The tissue-classified numerical model was developed in Brooks Air Force Base, Texas, USA [6]. It has a resolution of 1 mm. We combined 2 x 2 x 2 cells of the model to obtain a new resolution of 2 mm because a 2-mm cell size is sufficient at 900 MHz band. We decided the tissue classification for each new 2-mm cell by the major tissue in that cell. Fig.4 gives a visualization of the human model, together with a 900 MHz mobile phone model, i.e., a 1/4-wavelength monopole antenna mounted on a metal box. It should be noted that the hand grasping the mobile phone was not simulated at present due to the difficulty in modifying the whole body model. The total computation volume includes 340 x 220 x 1000 cells, and it took ten time periods to achieve the steady state. As a result, the run time was 8.5 hours and the memory required was 9 GB on our parallel system.

Fig.5 shows SAR distributions for the whole body model and the isolated head model. Except in the head, a considerable EM absorption also occurred in the shoulder indeed. However, compared to the isolated head model, no significant difference can be found for the SAR distribution inside the head. Table I gives the one-gram and ten-gram averaged spatial peak SARs for an antenna output of 0.27 W at 900 MHz. As can be seen, there was not an increase in the whole body model, compared to the isolated head model, for the one-gram or ten-gram averaged spatial peak SAR. The body effect on the peak SAR was almost negligible, i.e., only 2.6%. The increased peak SAR reported in [5] may attribute to their highly simplified, inadequate human modeling in which the bottom of the mobile phone almost touched the elevated flat shoulder.

Table I Comparison of peak SARs in a whole body model and an isolated head model

	Whole body model	Isolated head model	Difference
One-gram peak SAR	1.32 W/kg	1.35 W/kg	-2.3 %
Ten-gram peak SAR	0.78 W/kg	0.80 W/kg	-2.6 %

#### 5. Conclusion

A parallel FDTD computation system has been developed on Linux-based personal computers using MPI library. For eight CPUs, a speed-up ratio of six and memory-down ratio of 7.9 (16GB memory at



Fig.4 A visualization of the whole body human model together with a 900 MHz mobile phone model.

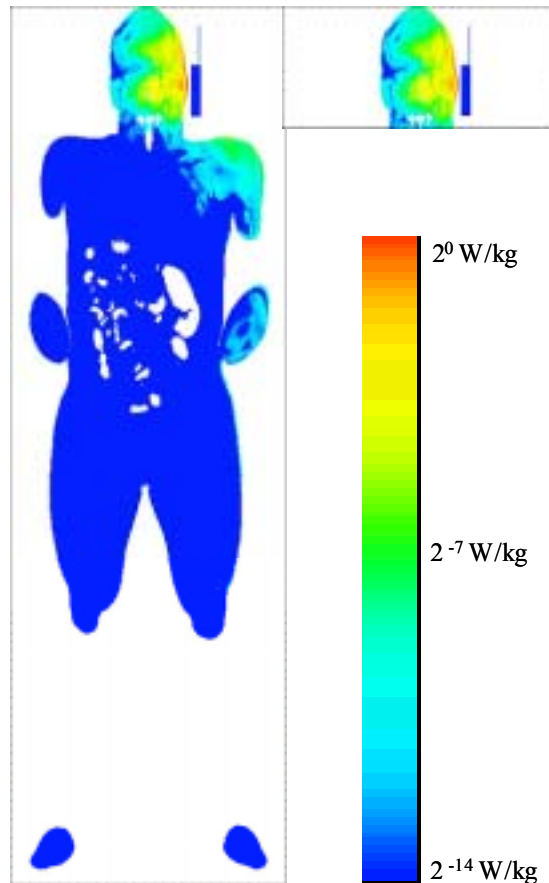


Fig.5 SAR distributions for the whole body model and the isolated head model. The antenna output power was 0.27 W.

maximum) have been realized. Its application to large-scaled numerical dosimetry is very promising. With the employment of the parallel computation system, the human body effect on the peak SAR evaluation for mobile phones has been analyzed, and has been found to be only within 2.6%. Raising further the computation speed and using the parallel computation system to real world large-scaled numerical dosimetric problems would be the further subjects.

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