Application of Huygens Subgridding Technique to Human Body Modelling

Maksims Abaļenkovs[1], Fumie Costen[1], Jean-Pierre Bérenger[2], and Anthony Brown[1]

[1] The University of Manchester, M60 1QD, U.K.
{m.abalenkovs, f.costen}@cs.man.ac.uk, a.brown@manchester.ac.uk
[2] Centre d'Analyse de Défense, 16 bis, Avenue Prieur de la Côte d'Or, 94114, Arcueil, France. jean-pierre.berenger@cad.etca.fr

Introduction

The issues of interest for both the academic and industrial Ultra WideBand (UWB) communities include biomedical imaging, safety assessment of the influence of complex UWB multi-input multi-output communication systems which operate close to human beings and UWB on-body sensors. The channel characteristics for these radio environments have to be understood prior to system development and optimisation for the practical applications. Very little is known about propagation characteristics in humans or such issues as multipath and fading effects in UWB systems, because this is a relatively new technology. Therefore, to study the transmission channel characteristics in a wide range of radio environments, it is necessary to simulate transient wave propagation in electrically large but finely-detailed and dispersive structures.

Unlike techniques such as the Method of Moments, the Finite Element Method, the Geometrical Theory of Diffraction and the Physical Theory of Diffraction, Finite Difference Time Domain (FDTD) methods offer the ability to analyse arbitrarily-complex, wideband problems. Some tissues in the human body have geometrically complicated fine structures, and their high relative permittivity makes the wavelength of interest shorter than the one in air. Therefore, in FDTD space a spatial sampling resolution is required for numerical modelling of the interior of the human body whilst the free-space can be sampled with approximately $9 \sim 15$ times of this spatial resolution. This means that the computational memory requirements can easily exceed that available, and prohibit rigorous study with adequate accuracy when the space of interest and its surroundings are spatially sampled at the ideal resolution.

To reduce the memory requirement, a variety of subgridding techniques have been proposed [1–6]. Many of these techniques focus on interpolation at the interface, and a computational procedure is simpler than other methods which require matrix inversion [7–9]. In these techniques, the coarse mesh regions have the same temporal discretisation as that in the fine mesh regions, minimising later instability. However, [10] proposes a method to overcome this inefficiency. Nevertheless, the ratio between the coarse and fine meshes in these schemes are usually limited to 5-fold variation, to minimise the spurious reflections at the interface.

The works [11, 12] have proposed a solid method, referred to as Huygens SubGridding (HSG), to connect these different mesh regions based on the Huygens-Kirchhoff principle [13]. The advantage of this method is the absence of a restriction on the ratio of spatial resolutions and a lack of significant numerical reflections from the interfaces between differ-
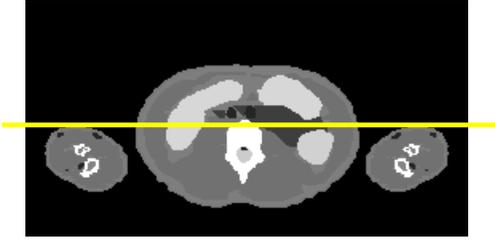
Figure 1: Cross section of subject NOR-MAN at 1.1 m from the ground. This MRI data has a 2 mm resolution model of NOR-MAN provided by Radiation Protection Division, Health Protection Agency, U.K.
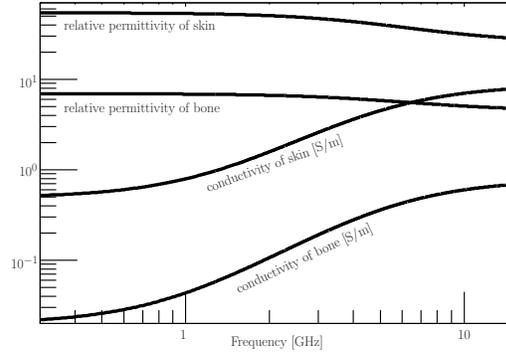
Figure 2: Example of frequency dependency of tissues in human body.
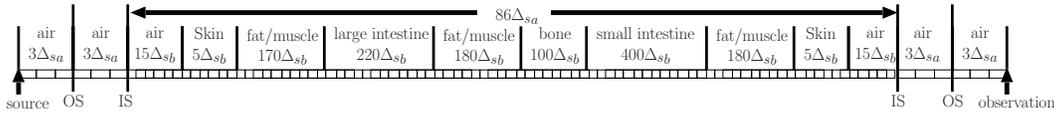
Figure 3: Numerical modelling for 1D FD HSG-FDTD.
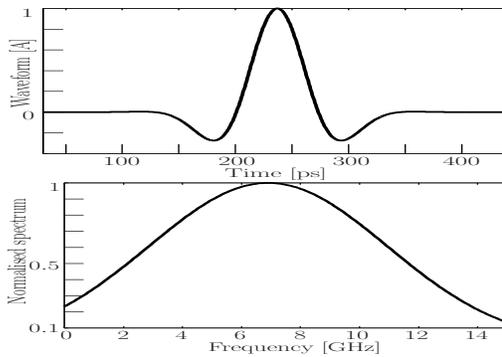
Figure 4: Source excitation in time and frequency domain.
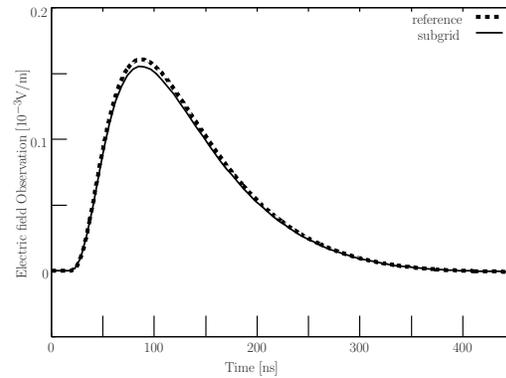
Figure 5: Observations

ent meshing regions. This paper applies 1D HSG-FDTD to the irradiation of UWB signals in the torso of a human body and discusses method's suitability as a first step towards realistic three-dimensional (3D) problems. The technical terminology on HSG in this paper is the same as in [11].

Numerical modelling

The radio environment for 1D HSG-FDTD was set based on Magnetic Resonance Imaging (MRI) data. The cross-section of a human torso is shown in Figure 1 and the material on the straight line is modelled in the FDTD space. It is assumed that the UWB signal is emitted about 4 cm away from the left hand side of the torso and propagates along the horizontal line in Figure 1. To validate the interface between the coarse and fine meshes, two sorts of numerical errors have to be distinguished: the error which might occur at Huygens surfaces and the error caused by numerical dispersion mainly in the coarse mesh. To

observe the error at the interface, the propagation distance in the coarse mesh should be minimised. Therefore, the distance between the source excitation and human body and the distance between the receiver and human body are deliberately and unrealistically short. In reality, the physical length of the total coarse mesh is longer than the physical length of the fine mesh to obtain the merit of the subgridding technique.

The frequency dependency of the tissues is modelled using the first order Debye model [14]. The relative permittivity ϵ_r and conductivity of the skin and bone modelled in the paper are shown in Figure 2. The central frequency to be used is 6.8 GHz and the corresponding wavelength is sampled by 9 points in every 5.88 mm in the air, defined as Δs_a. A single bone is about $7\Delta s_a$ in thickness. The relatively low ϵ_r means the bone can be implemented using the same spatial sampling as the air. In this case the wavelength of the central frequency would be sampled by about 4 points in the bone.

The skin has the thickness of 2 mm, which is the resolution of the MRI data. The skin can be modelled using $\Delta s_a/3$ without the media parameters being taken into consideration. In other words, one cell in the fine meshing can be used to model the skin when the subgridding region has a mesh ratio of 3. In reality, the modelling of the radio environment should be based not only on geometrical, but also on numerical, accuracy. To achieve a reasonable numerical accuracy, ϵ_r of the tissues has to be taken into account. For the skin, ϵ_r at 6.8 GHz is about 40, and the wavelength at 6.8 GHz in the skin becomes 8 mm. Very little numerical dispersion in the skin would be experienced if the wavelength is sampled by 20 points. The mesh ratio of 15 achieves this numerical accuracy. Therefore, this paper applies 1D HSG-FDTD with the mesh ratio of 15 to the propagation of UWB signal through a human body.

Numerical experiments

Various tissues on the horizontal line of Figure 1 are depicted in Figure 3. The entire body is modelled in the subgridding region and both the source excitation and the receiver are placed in the air in the coarse mesh. The source excitation is shown in Figure 4. The pulse is a modulated Gaussian and the centre frequency, whose frequency spectrum has the highest magnitude, is 6.8 GHz. The solid line in Figure 5 is the signal recorded at the observation point depicted in Figure 3. The dotted line in Figure 5 is the reference signal observed when the entire FDTD space from the source excitation to the observation has the same spatial resolution as the one in the fine mesh region in Figure 3. An energy difference of approximately 6 % and an approximately 3 % in the peak amplitude are observed between these two lines. This difference mainly comes from the numerical dispersion in the coarse mesh in Figure 3.

Conclusion

The modelling of media with high relative permittivity requires a spatial resolution finer than the one imposed by geometrical constraints. Such materials can be modelled efficiently in subgridding schemes. The ability of 1D HSG-FDTD to handle high meshing ratio allows the successful numerical modelling of a human body. This is the first step towards 3D modelling. Future work will target the efficient and accurate numerical modelling of the

References

[1] R. Kopecky and M. Persson, "Subgridding method for FDTD modeling in the inner ear," *Proc. SPIE*, vol. 5445, pp. 398–401, 2004.

[2] S. Wang, F. L. Teixeira, R. Lee, and J.-F. Lee, "Optimization of subgridding schemes for FDTD," *IEEE Microwave Wireless Comp. Lett.*, vol. 12, pp. 223–225, 2002.

[3] A. R. Zakharian, M. Brio, C. Dineen, and J. Moloney, "Second-order accurate FDTD space and time grid refinement method in three space dimensions," *IEEE Photo. Tech. Lett.*, vol. 11, pp. 1237–1239, 2006.

[4] B. Donderici and F. L. Teixeira, "Domain-overriding and digital filtering for 3-D subgridded simulations," *IEEE Microwave Wireless Comp. Lett.*, vol. 16, pp. 10–12, 2006.

[5] L. Kulas and M. Mrozowski, "Low-reflection subgridding," *IEEE Trans. Microwave Theory Tech.*, vol. 53, pp. 1587–1592, 2005.

[6] A. Vaccari, R. Pontalti, C. Malacarne, and L. Cristoforetti, "A robust and efficient subgridding algorithm for finite-difference time-domain simulations of Maxwell's equations," *J. of Computational Physics*, vol. 194, pp. 117–139, 2004.

[7] N. V. Venkatarayalu, R. Lee, Y.-B. Gan, and L.-W. Li, "A stable FDTD subgridding method based on finite element formulation with hanging variables," *IEEE Trans. Antennas Propagat.*, vol. 55, pp. 907–915, 2007.

[8] R. A. Chilton and R. Lee, "Conservative and provably stable FDTD subgridding," *IEEE Trans. Antennas Propagat.*, vol. 55, pp. 2537–2548, 2007.

[9] M. Marrone and R. Mittra, "A new stable hybrid three-dimensional generalized finite difference time domain algorithm for analyzing complex structures," *IEEE Trans. Antennas Propagat.*, vol. 53, pp. 1729–1737, 2005.

[10] K. Xiao, D. J. Pommerenke, and J. L. Drewniak, "A three-dimensional FDTD subgridding algorithm with separated temporal and spatial interfaces and related stability analysis," *IEEE Trans. Antennas Propagat.*, vol. 55, pp. 1981–1990, 2007.

[11] J.-P. Bérenger, "A Huygens Subgridding for the FDTD method," *IEEE Trans. Antennas Propagat.*, vol. 54, pp. 3797–3804, 2006.

[12] ——, "A FDTD Subgridding based on Huygens Surfaces," in *IEEE Int. Symp. Antennas. Propagat.*, 2005, pp. 98–101.

[13] C. Huygens, *Treatise on Light*. http://www.gutenberg.org/etext/14725, 1690.

[14] J. Costa, F. Costen, J.-P. Bérenger, and A. Brown, "Inclusion of frequency dependency in the Huygens Subgridding FDTD for UWB systems," in *IEEE AP-S Int. Symp.*, June, 2007.