Large scale Maxwell equation solver for UWB systems

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I. PREVIOUS RESEARCH TRACK RECORD

This is a joint application by the School of Electrical and Electronic Engineering (EEE) of University of Manchester (UoM), and the Centre for Communications Research (CCR) of the University of Bristol (UoB). It is concerned with algorithm development for three dimensional (3D) full-wave time domain Maxwell equation solvers.

The **Principal Investigator (PI)** Fumie Costen (formerly Fumie Taga) is a lecturer in EEE, and a member of the Microwave and Communication Systems (MACS) Group, at the University of Manchester. The PI's research interests include development of Computational ElectroMagnetics (CEM) for Ultra Wide Band (UWB) signals. The PI's background includes the introduction of Frequency Dependent (FD) media into the Finite Difference Time Domain (FDTD) method [1], speedup of full wave solvers [2] and accuracy assessment of models [3], [4]. The PI's research includes the metacomputing field [5], [6], an intercontinental network of supercomputers, where she proposed a management procedure of heterogeneous clusters of supercomputers. The PI received a best paper award in the International Conference on High Performance Computing (HPC) and Networking in 2000. Lastly, the PI has worked in the application of super-resolution algorithms to fault localisation in optical fibres and MMICs [7] and 3D laser microvision [8], [9]. This also includes research in image reconstruction for subsurface radar probing underground using radio waves. PI is a holder of 3 patents on 3D Laser Microvision.

The **Co-investigator (CoI1)** Anthony K. Brown is a Professor in the School of EEE at UoM. CoI1 joined academia 5 years ago having spent 28 years in industry, most recently for Easat Antennas Ltd where CoI1 is retained as part time Chairman. CoI1 is a recognised expert in CEM, especially as applied to Antenna and Propagation (AP) problems. He has been a Steering Board member of the Applied Computational Electromagnetics Society (ACES, USA) and is past recipient of the ACES Founders Award. CoI1 has served on a number of national and international committees (including for IEEE and IEE), relating to CEM, AP, and radar and communications topics. CoI1 was a member of the Technical Advisory Commission to the Federal Communications Commission (FCC) until 2006 - the only non-US member. He is a frequent invited lecturer on CEM and related topics, most recently on the application of such techniques to UWB communications. CoI1's recent research centres on the UWB systems for communications [10], [11] and he is co-editor of a recent book on this subject.

The **Co-investigator (CoI2)** Ian Craddock is a Reader in CCR of UoB. CoI2 has research interests in antenna design, antenna arrays, electromagnetics and radar and has published over 100 papers and 2 book chapters on UWB antennas. He heads a world-leading team working on breast cancer detection with UWB Radar [12], employing a 31-element curved antenna array [13] and human body phantom, work for which he received in 2005 the IEE's J. A. Lodge Award, and for which the team was subsequently awarded the 2006 IET Innovation award. CoI2 was recently awarded over £700k of funding from EPSRC to continue this work through to 2011, along with a further £250k for collaboration with the Institute of Biomedical Engineering at the University of Oxford. CoI2 has delivered numerous invited papers to conferences in Europe, North America and Asia, has convened and chaired sessions at these conferences and was recently the chairman of the 2007 European Workshop on Conformal Antennas in Bristol. CoI2 also has a long background with FDTD[14], contributing a number of papers to its theoretical advancement, along with its practical application. CoI1 and CoI2 represent the UK in the COST ASSIST Action.

The **Co-investigator (CoI3)** is Professor Chris Railton in CCR of UoB. In addition to FDTD, where he has pioneered a number of new techniques to advance the state of the art [15], he has been active in other modelling techniques, especially the Spectral Domain Method and Partial Element Equivalent Circuits, and in the development of hybrids consisting of electromagnetic, thermal and semiconductor models. He has published over 90 journal and conference papers in this area and has been an invited speaker at numerous international conferences.

This project provides an opportunity to bring together the PI's expertise in the algorithm development for FD-Alternating Direction Implicit (ADI) -

FDTD, CoI1's expertise in mathematical skills for CEM, the expertise of CoI2 and CoI3 in FDTD and its practical application. The Universities' effort will be complemented by a collaborator with Mr. J.-P. Bérenger in Center D'Analyse de Défense in Paris, who is a leading international authority on FDTD in particular in boundary condition problems.

The **MACS group** at UoM currently comprises 14 full-time academics. Within the wireless communications discipline the group has wide interests concentrating on the physical layer and including UWB AP, HF radio systems, system coexistence studies and wireless capacity improvements using innovative modulation and coding. The group includes the Electromagnetics Centre which was established by a EPSRC JIF grant of £1.84M for Microwave and Millimetre-wave Design and Applications. MACS is a part of the RAE 5 rated E&EE of the University of Manchester.

The **CCR** at Bristol was established by Professor McGeehan in 1984 and comprises over 150 people. CEM has been a strong focus for the CCR and the team has almost 20 years of experience with FDTD. Its work on FDTD algorithms for curved surfaces and for the treatment of sharp field gradients at edges has frequently been in advance of any other group in the world. The CCR's work on UWB breast cancer detection is well-known and in addition to a clinical prototype radar this includes curved breast phantoms, with skin, that are unique.

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II. DESCRIPTION OF THE PROPOSED RESEARCH

A. *Background and Context of the proposed research*

The aim of this proposal is algorithm development for the analysis of Ultra Wide Band (UWB) signals [16] propagating in complex, electrically-large, radio environments containing geometrically-fine objects.

The outcome of this project will be a major breakthrough for computation in electromagnetics, for problems which need to simulate transient wave propagation in electrically large but finely-detailed and dispersive structures. Some examples currently of great interest are biomedical imaging, safety assessment of the influence of complex UWB multi-input multi-output communication systems operating close to human beings, UWB on-body sensors and Ground Penetrating Radars (GPR).

Particular consideration will be given to solving these computationally-massive problems using low-cost high-throughput Distributed Memory Architectures (DMA). This results in a linkage between the algorithm development from the electromagnetics viewpoint, the application requirements and the computational science discipline. The research team assembled for this proposal provides the necessary mixture of skills.

The focus of this proposal is on enhanced Finite Difference Time Domain (FDTD) methods for the numerical dosimetry of UWB signals inside the human body, not UWB indoor propagation. These offer the capability of analysing arbitrarily-complex, wideband problems, unlike methods such as the Method of Moments (MoM), the Finite Element Method (FEM), the Geometrical Theory of Diffraction (GTD) and the Physical Theory of Diffraction (PTD). The detail required for the numerical modeling of our application is too complicated to be handled by GTD. In particular, UWB system analysis requires the examination of waveform distortion in the time domain during propagation in a wide range of dispersive media. Methods such as MoM and FEM mainly work in the frequency domain, requiring repetition of simulations, sweeping the frequency of interest to construct a single waveform in the time domain.

Unlike MoM and FEM, FDTD and Frequency Dependent (FD) - FDTD [17] works in the time domain and is capable of explicitly computing macroscopic transient electromagnetic interactions with general 3D geometries. Furthermore in FD-FDTD, the medium parameters such as permittivity and conductivity vary with frequency which is important for the UWB simulations. FD-FDTD is the simplest method among a variety of techniques to produce the time domain signal in the frequency dependent media. Thus, FD-FDTD is the most suitable for UWB system modelling. Therefore, this project chooses FD-FDTD as the main technique to solve the problems.

The main difficulties in the use of FD-FDTD are long execution time and high memory requirements when the simulation contains geometrical features that are electrically small relative to a large physical space.

To take an example from UWB In-Body communications, fat and intestine in the human body have a relative permittivity of 40 at 6GHz. In the lossy media, the wavelength becomes as short as 8mm at 6GHz. To achieve the reasonable numerical accuracy in FDTD, the spatial resolution therefore has to be 0.4mm (= 8mm / 20) although the minimum resolution from an MRI scan is 2mm. Assuming that a volume of a slice of a human body to be modelled is 50cm×50cm×40cm, 1.5×10^9 FDTD cells would be required and this would require at least 290 GB of memory. *This level of memory requirement simply prohibits the rigorous study of In-Body communication with adequate accuracy.*

Bearing in mind these massive computational requirements, many studies have attempted to improve FDTD for faster calculation and memory reduction. For example, a FDTD calculation region (window) can be shifted over a large distance in one direction to model propagation of localised wave-packets [18]. Subgridding techniques have also been proposed [19] which divide the simulation space into a number of subspaces. In the non-uniform FDTD method [20], a distortion of the grid is employed by the non-orthogonal FDTD method [21] to fit meshing to the known material geometry with a grid size larger than the standard FDTD for the same order of accuracy.

While these techniques have much to offer, the maximum value for a temporal discretisation Δt is limited by Courant-Friedrichs-Lewy (CFL) stability condition [22]. Therefore, these methods do not give significant impact on the reduction of required computational resources.

The application of the ADI method to FDTD [23] and FD-FDTD [2] achieves a reduction of computation time by removing CFL condition on the time-step, with Δt theoretically hundreds times larger than the Δt limited by CFL condition in standard FDTD. (Note that the so-called envelope ADI-FDTD [24], however, is not relevant to this project as it is specialised to narrowband systems.)

FD-ADI-FDTD requires special attention to both the treatment of the boundaries and to numerical noise. Among the various Absorbing Boundary Conditions (ABC) which have been studied for the standard FDTD, the Mur 1st Order ABC [25] is the most simple but offers low absorption, whereas the Complex Frequency Shifted (CFS)[26] - Perfectly Matched

Layer (PML) [27] ABC while very complex does give high absorption. Although simple ABCs need a large margin between the boundaries and the objects, the computational load is relatively low and the memory requirement for the calculation of the ABC is small compared with the calculation for the interior space. On the other hand, the computational load and memory requirement is high for the highly-absorbant ABCs but the objects can be placed a couple of FDTD cells away from the ABC after the complicated optimisation of simulation parameters.

CFS-PML ABC has never been successfully evaluated for FD-FDTD and FD-ADI-FDTD. Therefore, this project investigates the applicability and practicability of CFS-PML ABC toward FD-FDTD and FD-ADI-FDTD.

Regarding numerical noise, all finite differencing schemes experience Numerical Dispersion (ND) [28], [29]. The ADI scheme splits each full FDTD step into two half steps, each involving solution of a tridiagonal matrix [30]. This procedure causes splitting [31] and truncation [32] errors, resulting in increased ND. These errors depend on both Δt and a sudden change in field distribution. This fact becomes problematic when material or structural inhomogeneities introduce spatial variations in the fields that are on a much smaller scale than that of the wavelength of the source excitation. Thus, acceptable ND caused by the ADI scheme sets an upper limit on Δt [4]. *Typically Δt in the ADI scheme could be 4 $\sim$ 10 times as much as Δt of the upper limit for the CFL stability condition*. Thus, FD-ADI-FDTD alone does not lead to a drastic improvement in computation time and memory requirements.

Larger time steps may be tolerated, provided that large numerical spatial derivatives are avoided. This requires careful treatment of the rapid field variations in proximity to small objects and sharp edges. This is precisely the area of expertise developed at CCR during the last 20 years [14] [15].

Parallelisation of FDTD has also been investigated. [33] discusses 1D FDTD parallelism on a workstation cluster with Parallel Virtual Machine (PVM) for inter-processor messages. [34] utilises a non-dedicated cluster of Sun workstations with PVM for parallel FDTD. [35] makes use of a cluster and the MPI protocol. This computational environment is also adopted for parallel 2D FDTD in [36] and parallel 3D FDTD in [37]. [38] chooses a single-instruction multiple-data (SIMD) platform for parallelism of 3D FDTD.

These approaches to parallelism increase the total tractable number of cells. From the viewpoint of reducing the elapsed simulation time and managing cell numbers, *the parallel FD-ADI-FDTD approach is the most promising*.

The amount of memory required for FD-ADI-FDTD could easily exceed 100 GB. However The maximum memory shared by 8 CPUs in a supercomputer in MC is only 16 GB. Thus, this required memory capacity becomes prohibitively expensive for Shared Memory Architectures (SMA), and this project focuses on DMAs.

Parallelism of the ADI scheme has indeed already been attempted once on a SMA [39]. [40] parallelised their subgridding scheme which is the combination of ADI-FDTD and conformal FDTD. However, in that research only the conformal FDTD space is parallelised, leaving the ADI-FDTD subspace in a single partition assigned to a single computational node. This approach is clearly non-optimal in the general case and completely fails at the point where ADI-FDTD space is larger than the capacity of one node in which multiple cores share a memory.

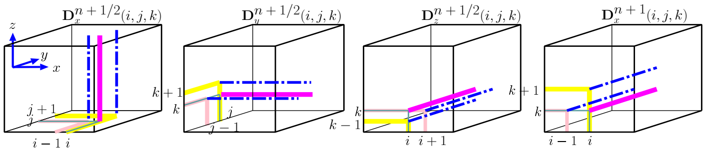
B. Programme

1) Aims: The aim of this project is to develop
a) algorithms to reduce ND in FD-ADI-FDTD;
b) algorithms for spatial division in the interior space of FD-ADI-FDTD and the boundaries for parallelisation, and
c) techniques to handle load-balancing on non-dedicated DMAs.
Computational accuracy will be evaluated by numerical simulations of medium-scale serial and small-scale parallel FD-ADI-FDTD code run on a SMA and by comparison with the real measurement data obtained in CCR.

The investigators have access to large scale Dual Core DMAs: North-West Regional Grid (NW-GRID) (`www.nwgrid.ac.uk`), the National Grid Service (NGS) cluster (`www.ngs.ac.uk`). The investigators also have access to the IBM Baby Blue Crystal machine in the Advanced Computing Research Centre at the University of Bristol and IBM has offered access to a massively parallel BlueGene system (See attached letter). These machines will be used to provide additional evaluation and comparative data for computational efficiency, scalability and practical usability.

2) Objectives:

Obj1a To develop a spatially parallel FD-ADI-FDTD



Field values on three lines; $(x,y)=(i,j)$, $(i-1,j)$, and $(i,j+1)$ update $\mathbf{D}_x^{n+1/2}$ on a line $(x=i,y=j)$
Field values on three lines; $(x,z)=(i,k)$, $(i-1,k)$, and $(i,k+1)$ update $\mathbf{D}_x^{n+1}$ on a line $(x=i,z=k)$

Fig. 1. The grid link for update of FD-ADI-FDTD

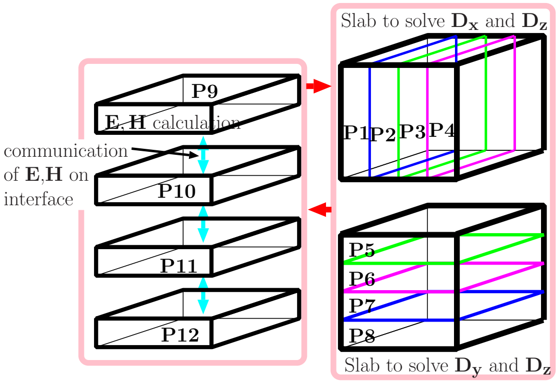
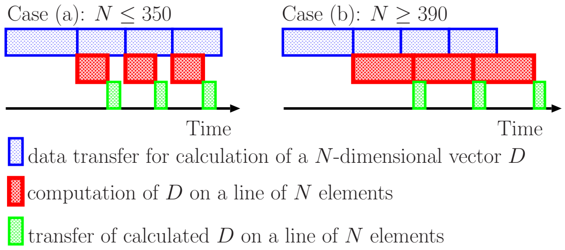


Fig. 2. Proposal on partitioning of FD-ADI-FDTD



▨ data transfer for calculation of a N-dimensional vector D
🟥 computation of D on a line of N elements
🟩 transfer of calculated D on a line of N elements

Fig. 3. Data flow for computation of a N dimensional vector $\mathbf{D}$

with Mur ABC on a DMA,

Obj1b To seek a generic, adaptable implementation of this algorithm that is efficient across a range of current and anticipated parallel DMA computer architectures,

Obj2 To develop an alternative algorithm to FD-ADI-FDTD which has higher accuracy for larger Δt and irregular Δs than achieved by current FD-ADI-FDTD,

Obj3 To develop algorithms to adapt CFS-PML ABC to serial FD-FDTD,

Obj4 To develop algorithms to adapt CFS-PML ABC to serial FD-ADI-FDTD,

Obj5a To develop a spatially parallel FD-ADI-FDTD with CFS-PML ABC on a DMA,

Obj5b To seek a generic, adaptable implementation of this algorithm that is efficient across a range of current and anticipated parallel DMA computer architectures.

C. Methodology

This project seeks algorithms

1) to parallelise FD-ADI-FDTD on DMA to achieve both an increase in the tractable cell number in the FDTD space and a decrease in the total elapsed time;

2) to suppress the numerical noise caused by Δt larger than the one currently acceptable in the FD-ADI-FDTD scheme; and

3) to apply CFS-PML ABC to FD-ADI-FDTD to reduce the total grid number and to increase accuracy.

FDTD updates $\mathbf{E}$ and $\mathbf{H}$ at a point utilising field values at three adjacent points. Thus, FDTD has a high degree of parallelism that can be exploited easily. On the other hand, the ADI scheme loses independence in one of three space dimensions. Fig. 1 shows the data region required for an update of the electric flux density $\mathbf{D}$ in the FD-ADI-FDTD scheme. The tridiagonal system to determine $\mathbf{D}$ consists of field values on the three adjacent lines. The directions of these lines to solve $\mathbf{D}_x$, $\mathbf{D}_y$ or $\mathbf{D}_z$ differ as shown in Fig. 1. *No fixed mapping of space points to CPUs will keep coupled points on the same CPU over a full time step*. Thus, space division in FD-ADI-FDTD requires a major algorithmic modification for the treatment of the tridiagonal matrix.

This project proposes an integrated solution where the transposition becomes part of the solver to obviate the sudden demands that would otherwise be placed on the communications system. In the integrated solution, the FD-ADI-FDTD space is divided into slabs in two ways as shown in Fig. 2. The data in each slab is sent to each node for $\mathbf{D}$ calculation. Since calculation of $\mathbf{D}$ on a line requires only the data on three adjacent lines, the node starts the calculation as soon as the data required for a calculation of $\mathbf{D}$ on a line is received as shown in Fig. 3.

The nodes calculating $\mathbf{D}$ *continue to receive the*

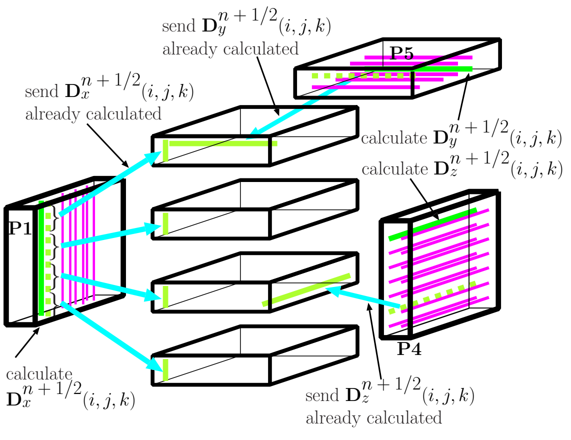


Fig. 4. Overlap of communication and calculation in FD-ADI-FDTD

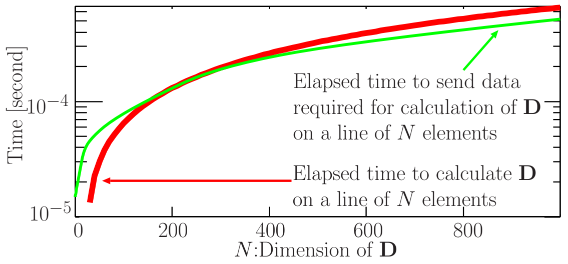


Fig. 5. Time to transfer data for computation of a N dimensional vector $\mathbf{D}$ and time to calculate a N dimensional vector $\mathbf{D}$. The time is measured using two computers which are connected via dual Gigabit Ethernet. Each machine has a 2.4 GHz dual-core CPU, 1MB of cache, and 8 GB of memory.

rest of the data in the slab and send the calculated $\mathbf{D}$ back to different slabs where the electric field $\mathbf{E}$, the magnetic field $\mathbf{H}$ are calculated, as is depicted in Fig. 4. By using asynchronous communication it will be possible to *overlap communication and computation fully*. $\mathbf{H}$ calculation requires only slight communication of $\mathbf{E}$ at the interface between the slabs, as is done in the parallel FDTD calculation. A similar approach has been successfully demonstrated in the parallelisation of the Jodrell Bank de-dispersion pulse search code [41], [42]. Communication will be implemented using single-sided MPI messages.

The feasibility of the proposed method is evaluated by measuring the elapsed time (thick line in Fig. 5) to calculate a N dimensional vector $\mathbf{D}$ in (N grids)^3 cubic FDTD space and the time (thin line in Fig. 5) to transfer the data required for the computation of a N dimensional vector $\mathbf{D}$. Fig. 5 suggests that the case (a) with $N \leq 350$ in Fig. 3 will result in the existence of the dead time in a node's activity but the node carries out the successive work without dead time with $N \geq 390$. The available memory at each node limits N; the upper limit of N is about 210 in case of the single core machine with 2GB of memory. Therefore, the approach to the problem described above is feasible only when the amount of a shared memory in each node on a DMA is significantly larger than 2GB. There may be an alternative solution for the spatial division. Thus the purpose of the research here is to investigate techniques to divide an entire space into subspaces in FD-ADI-FDTD with minimum degradation of accuracy in handling the tridiagonal matrix on DMAs taking into account problems associated with communication, data passing and synchronisation between nodes.

In addition to the benefits to be gained from the efficient use of parallel processing, there is much scope for improvement of the basic algorithms. ND limits the size of Δt and Δs (Δt and Δs are the temporal and spacial discretisation sizes respectively), because of accuracy considerations, leading to limited processing speed and FDTD space. Reduction of ND by modification of the basic algorithm of FD-ADI-FDTD will enable larger Δt and variable Δs settings. The accumulated techniques in CCR for the reduction of ND [14], [15] are well placed to address the challenge of suppression of ND in FD-ADI-FDTD. The major objective of this project is to devise an efficient, feasible space division procedure in FD-ADI-FDTD with low ND on DMAs. Although clusters do not have the low latency and very high bandwidth of more specialist and expensive custom-designed HPC computers, our previous work in metacomputing over wide area networks[42] utilised algorithms that overlap computation and message sending to mitigate these limitations.

The outcome will combine CCR's expertise in efficient, novel, FDTD algorithms with the efficient parallel implementation techniques and methodologies and techniques to deal with frequency dependent materials in EEE, to yield uniquely powerful electromagnetic analysis software with an efficient, feasible space division procedure in FD-ADI-FDTD on various DMAs. This will enable a wide range of UWB research such as in-body communications and microwave imaging to be performed at *higher accuracy than currently available methods*. The accuracy of the analysis tool for UWB technology is verified by comparison between the numerical simulation results and the measurement campaign at CCR.

The hybrid work (combination of FDTD and ADI-FDTD), such as [43] and [40], which left the ADI-FDTD subspace unparallelized in IBM BlueGene at Astron, will benefit greatly from combining the outcome of this project with their technique to connect parallel FDTD and ADI-FDTD.

This proposal is at the leading edge of the technology. As can be seen from the above, the proposers have accumulated considerable expertise in FDTD, FD-ADI-FDTD and computer clustering, which gives the project on algorithm development of parallel FD-ADI-FDTD with low ND a great chance of success.

D. *Work units*

The first Work Package **WP(I)** is the algorithm development of FD-ADI-FDTD with Mur ABC. The initial objective is to develop a parallel algorithm for a DMA, with a longer-term objective of developing an adaptable (autonomous) implementation that is robust and efficient across a range of current and anticipated parallel computer architectures.

I.1 reviews the in-house serial FD-ADI-FDTD with Mur ABC.

I.2 performs theoretical study toward parallel FD-ADI-FDTD with Mur ABC on DMAs. WP(I.2) will develop a full 3D domain decomposition for ADI-FDTD.

PI has significant experience in performance analysis and improvement for large, parallel, scientific codes as well as performance control techniques for large-scale, distributed scientific applications.

This experience will be made available to **I.2**, **I.4**, **IV.2**, and **IV.5** of this project for the support of the PDRA in the project.

I.3 codes the parallel 3D FD-ADI-FDTD with Mur ABC to achieve **Obj1a**. While the parallel FDTD developed in [37] runs only on a fixed number of CPUs, this project aims to develop as flexible a code as possible. The ultimate objective is to develop a robust and efficient implementation that can adapt to any particular parallel architecture **Obj1b**.

I.4 optimises the simulation parameters for 3D parallel FD-ADI-FDTD with Mur ABC and evaluates the performance on various architectures.

WP(II) addresses the treatment of boundary conditions with the aim of improving accuracy and increasing the physical space for objects. The superiority of CFS-PML ABC over Mur 1st ABC enables source excitations and scatterer to be placed closer to ABC, leading to an increase of physical modelling space.

II.1 develops the algorithm to adapt CFS-PML ABC to serial FD-FDTD in collaboration with Mr. J.-P. Bérenger.

II.2 implements the serial FD-FDTD with CFS-PML ABC and assesses the performance of the ABC over Mur ABC from the perspective of reflection coefficient, parameter tuning in lossy media and required memory, to achieve **Obj3**.

II.3 will include CFS-PML ABC in serial FD-ADI-FDTD.

If II.2 decides not to adopt CFS-PML ABC, then II.3 will study the performance of CFS-PML ABC and/or difficulties in tuning the CFS-PML parameters.

II.4 develops the serial FD-ADI-FDTD algorithm with CFS-PML ABC to achieve **Obj4** and assesses the stability in lossy media and the achieved reflection coefficient.

WP(III) develops algorithms to suppress the numerical dispersion of 3D serial FD-ADI-FDTD for large Δt.

III.1 undertakes a theoretical study of conventional methods to suppress numerical dispersion in 3D FD-ADI-FDTD with Mur ABC.

III.2 develops algorithms to suppress numerical dispersion of 3D FD-ADI-FDTD with Mur ABC by applying our expertise in FD-ADI-FDTD algorithm development, subgridding, fine geometrical detail and graded meshes.

III.3 implements the algorithm for the numerical dispersion reduction to the serial 3D FD-ADI-FDTD with Mur ABC to achieve **Obj2**. The radio environment for the real measurement with human body phantom is numerically modelled, and is used for the test of the parallel 3D FD-ADI-FDTD with Mur ABC code. The calculated results will be compared with real measurements from modelling for breast cancer detection.

III.4 optimises the simulation parameters for the suppression of numerical dispersion and asymmetry propagation in the serial 3D FD-ADI-FDTD with Mur ABC.

WP(IV) merges the outcomes from WP(I), WP(II) and WP(III) to achieve the 3D parallel FD-ADI-FDTD with CFS-PML with less numerical noise.

IV.1 implements and evaluates the modification of the suppression of the numerical dispersion into the 3D parallel FD-ADI-FDTD with Mur ABC.

IV.2 performs a feasibility study on the parallelism of CFS-PML ABC. If CFS-PML ABC is used in FD-ADI-FDTD, a theoretical investigation of the parallelism of CFS-PML ABC is carried out. [38] abandoned parallelism of PML due to its complexity and no work, to date, has investigated the technique of CFS-PML ABC in parallel systems. Therefore, incorporation of CFS-PML ABC into this parallel 3D FD-ADI-FDTD code will be pursued to identify difficulties in its implementation. This will be realized initially by separation of FDTD interior region and PML exterior region. The applicability of the parallelisation strategy of the FD-ADI-FDTD with Mur ABC to the PML exterior region will be examined. If this parallelisation strategy is not applicable, then IV.2 modifies the parallelisation strategy to accommodate CFS-PML ABC.

IV.3 implements the parallel CFS-PML ABC for FD-ADI-FDTD with numerical dispersion suppressed to achieve **Obj5a** and **Obj5b**.

IV.4/IV.5 validates the simulation parameters optimised in serial FD-ADI-FDTD with CFS-PML ABC in the parallel system. The application will be fully robust and will be be assessed in terms of numerical accuracy and stability, as well as computational efficiency, on multiple computer architectures that are available to the project.

WP(V) produces the phantom model and performs the measurement campaign. The geometry and material property of the phantom is passed to Manchester for the numerical simulation. The results of the measurement campaign are used in IV.4 and IV.5 for the validation and the accuracy assessment of the scheme developed in this project.

E. *Expected outcome*

This project will extend generic knowledge, as well as engineering information, about the feasibility of novel algorithm development of 3D FD-ADI-FDTD on DMAs. In particular, it will include (1) a proof of concept demonstration; (2) evaluation of system parameters: accuracy of simulation, total elapsed time, the number of tractable cells.
This evaluation is compared with the result obtained from the serial code and from non-dedicated clusters, as well as real measurements.

F. *Significance*

When applied to many interesting problems, Maxwell equation solvers require both long computational run times and, frequently, an impractically large memory. Among such methods, FD-ADI-FDTD method is the currently available scheme which handles the UWB system with the minimum total elapsed time. For an electrically large radio environment it also demands large memory, not available on a single desktop computer. Although the use of a supercomputer is one way to address this problem, such architectures are not generally available. The adaptable software that we will develop to parallelise 3D FD-ADI-FDTD to accommodate an electrically large scale radio environment on any DMAs, with practical levels of elapsed time and accuracy, would represent a significant advance in the state of the art.

G. *Relevance to beneficiaries*

The potential impact of the proposed work for a wide range of UWB applications such as medical imaging could be significant for both the academic community and the UWB industrial sector. This work will also provide enhanced performance in the radar application such as GPR that can be used for mine clearance operations. Improved performance of FD-ADI-FDTD will benefit world leading developers of UWB technologies. The knowledge and tools developed in this project will be passed on to industry through MACS's many industrial contacts and partners. This will allow industry to become a market leader in UWB systems. The research will help to maintain Europe, and in particular, the UK at the forefront of the technology in CEM, especially UWB systems. Since this is generic research, research communities such as ASSIST (successor of COST284) will benefit from its applicability to other fields. UoM and UoB will enhance their reputation through publication of results and the students will gain a better understanding of problems through contact with the research of teaching staff.

H. *Dissemination and exploitation*

The results of this research will be published in academic journals such as J. Parallel Distributed Comp. and IEEE Trans. on Antennas Propagat., Electromag. Compat. and Parallel Dist. Syst. and refereed international conferences such as IEEE APS, IMS, ICPP or ICPADS and presented to research networks such as ASSIST. Our publication records will testify to our success in having our work published in the most appropriate media. Exposure to the wider public will occur through entries in publicly accessible websites of the MACS group. Since the code will have high portability, as it will be developed in Fortran under the Linux environment, the research community can benefit from this project straightforwardly. UoM Intellectual Property Limited is also used for the university's technology transfer and intellectual property commercialisation.

III. SUMMARY

This collaborative proposal brings together the unique strengths of a number of different internationally-leading teams in highly research-intensive Universities. A powerful, versatile and ground-breaking analysis tool for UWB technology will be built during this project and have significant impact on both the academic community and UWB industry. The parallelisation technique to be developed will also be highly applicable to other implicit schemes used to solve partial differential equations.

Justification of Resources

A. Directly Incurred

1) Personnel: The project goal is the comprehensive study of a novel technology for parallelism of 3D FD-ADI-FDTD on DMAs. This will be achieved not only by highly mathematical investigations of the theory but will also involve practical method of computer simulations with competent implementation skills because development of ADI-class source code is extremely difficult and time consuming as is experienced by PI and elsewhere[30]. The project is considered to be highly adventurous but challenging both in the theoretical algorithm development and numerical experimental aspects. Thus a 3-year full-time Post-Doctoral Research Associate (**PDRA**) is necessary to undertake theoretical work, computer and mathematical modelling. This project expects PDRA to have intensive research experience on FDTD and fair knowledge of software engineering field. Given the high demands placed upon PDRA and the level of experience required, we are requesting an appointment at Grade6-Point4(G6P4) level. In addition, one RA is requested:

100% of RA **RA2** for 2 years is from CCR. RA2 will work with PDRA to develop algorithms, and will provide the numerical radio environment setting to PDRA for the numerical experiments and assess the numerical results obtained by PDRA against the real data measured by RA2. The same level as PDRA is requested for the same reason.

2) Equipment at EEE: Since a major task of this project is algorithm development, it will be necessary to perform a majority of tasks on a local workstation, equipped both multiple cores and multiple CPUs to perform both serial and parallel code testing. Small test case needs to model at least 50cm×50cm×4cm to cover the slice of the human torso at 6 GHz which requires at least 29 GB of memory. Thus PDRA will require a dedicated workstation with Two Quad Core and 32 GB RAM such as Dell Precision 690n(£12868) for the implementation of both serial and parallel codes and the numerical experiments. HPC is not used for the code development stage as it has low throughput. The Intel Fortran Compiler (IFC) is required because it is a robust compiler with good parallel support (£410×1 license=£410). IFC is not free of charge even for the education sector.

PDRA, and RA1 requires a desktop PC Dell Optiplex 740(£549 × 2 = £1647). and RA2 an equivalent Viglen system (£645).

3) Travel cost and consultancy fee for a visiting researcher, Mr. J.-P. Bérenger: It is planned to collaborate with a leading international authority, Mr. J.-P. Bérenger in Center D'Analyse de Défense in Paris. His advice on the treatment of ABC and numerical noise assessment will help this project more rapidly to achieve its objectives. The communication between Mr. J-P. Bérenger and EEE will be performed using email and meeting in person. He is expected to visit Manchester for the technical discussions twice a year for 3 years. [Each visit with 2 nights stay in the UK requires return flight(£300), accommodation(£135) and meal(£65).] £500 × twice × 3 years = £3K will provide the opportunity to invite Mr. J-P. Bérenger for specific technical discussions.

4) Travel at EEE and CCR: It is planned to take part in International conferences: IEEE Antennas and Propagation Symp.(APS) once a year for 3 years, and Int. Conf. Parallel and Distributed Systems(ICPADS) once near the end of the project from EEE, and IEEE Int. Microwave Symp.(IMS) once a year from CCR for 2 years. [One person requires registration fee(£350=600 US$), return flight(£850), transportation in the UK and the US(£40), accommodation(£60=100 US$×8 nights), meal(£30×9 days) as extra days are usually required for travelling to obtain the cheaper flight tickets.] £2000×1 person×6 times for 3 years = £12000.
It is planned to have 4 meetings per year for 2 years between Bristol and Manchester. Half of the meetings involve the travel of one RA and the other half involve the travel of 2 people. [One person requires saver return train tickets(£60), accommodation(£60), meal(£30).] £150×6 people×2 years=£1800.

5) Consumables for EEE and CCR: General Stationery £1500 for EEE, and £1000 for CCR and journal page charges for £1000 for EEE and breast phantom components (perspex, oil, beeswax, epoxy resin, aluminium angle) for £500 for CCR.

B. Directly allocated

12 % of PI at EEE is requested for overall project management, technical supervision of PDRA, liaison of 2 sections(EEE, CCR), and control of publication plan and preparation for the publications. 4% of CoI1 at EEE is requested for advice on the analysis of the results from the numerical experiments, planning of the numerical experiments, publication plan. 4% of CoI2 and CoI3 for 2 years at CCR is requested for the supervision of RA2, advice on algorithm development for the numerical noise suppression of FD-ADI-FDTD and on real measurement.

Project schedule for 36 months and risk assessment. (the number at the top of the table is in month)

This collaborative proposal brings together the unique strengths of a number of different internationally-leading teams. A powerful and ground-breaking analysis tool for emerging UWB technology will be built during this project.

	$0 \Longrightarrow 6$	$6 \Longrightarrow 12$	$12 \Longrightarrow 18$	$18 \Longrightarrow 24$	$24 \Longrightarrow 30$	$30 \Longrightarrow 36$
EEE PDRA	II.1 Adaptation of CFS-PML ABC to serial FD-FDTD	II.2 Coding and practicality assessment of serial FD-FDTD with CFS-PML ABC	II.3 Adaptation of CFS-PML ABC to serial FD-ADI-FDTD	II.4 Coding and practicability assessment of serial FD-ADI-FDTD with CFS-PML ABC	IV.1 Coding the accuracy-improved parallel FD-ADI-FDTD with Mur ABC	IV.3 Coding of parallel FD-ADI-FDTD with CFS-PML ABC IV.4 Code validation and IV.5 Performance analysis
	I.1 Review of FD-ADI-FDTD I.2 Algorithm development for parallelisation of FD-ADI-FDTD	I.3 Implementation of parallel FD-ADI-FDTD		I.4 Optimization for parallel FD-ADI-FDTD and system assessment	IV.2 Parallelization of CFS-PML ABC	
CCR RA2		III.1 Literature survey	III.2 Algorithm development for the suppression of serial ADI-FDTD	III.3 Implementation of modification to serial FD-ADI-FDTD	III.4 Parameter optimization and code porting V Phantom measurement campaign	
EEE PI	Assist with transfer of existing knowledge to PDRA, advice on parameter selection for FDTD in UWB systems, lead preparation of results for publication and subsequent dissemination		Continually input the technical aspects of numerical experiments, advice on analysis and interpretation of data, assist theoretical algorithm development, parallelisation, matrix inversion treatment, advice on performance analysis on DMAs, lead preparation for publication			
EEE CoI1	Arrange project resources and finances overall, career monitor PDRA, advice on interpretation of results from numerical experiments, lead role in evaluating process, provide guidance on the development of numerical experiments					
CCR CoI3		Supervise programme in terms of algorithm development to suppress numerical noise experienced and radio environment setting for numerical simulation and assessment of simulators using the real measurement, jointly author papers				
CCR CoI4		Arrange project resources and finances overall, career monitor RA2, advice on interpretation of results from numerical experiments, jointly author papers				
Completion and Milestone		M1	M2	M3 M4	M5	M6 M7 M8

The program is balanced with high risk tasks for high quality research. The following is the detailed description, the leading group for each task and individual risk level of each milestone depicted in the table.

M1 is theoretical 3D FD-ADI-FDTD parallelisation with Mur ABC by EEE (low risk)

M2 is serial 3D FD-FDTD with CFS-PML ABC by EEE (low risk)

M3 is algorithm and code development of parallel FD-ADI-FDTD with Mur ABC by EEE (medium risk)

M4 is algorithm and code development for the numerical-dispersion suppressed serial FD-ADI-FDTD with Mur ABC by CCR (medium risk)

M5 is algorithm and code development of serial FD-ADI-FDTD with CFS-PML ABC by EEE (high risk)

M6 is algorithm and code development of parallel FD-ADI-FDTD with Mur ABC by EEE (low risk)

M7 is algorithm and code development of parallel FD-ADI-FDTD with CFS-PML ABC by CCR and EEE (high risk)

M8 is validation and publication of parallel FD-ADI-FDTD with CFS-PML ABC by EEE (low risk) and performance analysis and publication of parallel FD-ADI-FDTD with CFS-PML ABC by CCR and EEE (low risk)