Extended abstract: Efficient numerical boundary integral methods applied to the calculation of UHF radio propagation in wireless personal communications

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Abstract

Surface integral equations provide an elegant and compact formulation of electromagnetic wave scattering problems involving homogeneous scatterers imbedded in free space. In this paper we will formulate a practical UHF radio propagation problem as a surface integral equation and discuss efficient methods for its numerical solution. This presentation draws heavily from work previously published by the authors and in particular our recent ACES [1] paper.

I. Introduction

Planning a cellular land mobile radio communications network [2] is a complex task involving the use of topographic, morphographic and demographic data to determine the location and radio characteristics of (as well as the communications links between) a large number of base transceiver stations (BTS). The overall planning process is beyond the scope of this paper where we restrict our attention to the problem of the efficient computation of the electric field strength caused by a specified distribution of monochromatic sources (the BTSs). Moreover we will further limit ourselves here to the discussion of UHF propagation over irregularly undulating terrain which is only one of many possible radio environments which need to be considered in radio planning.

The approach modelling of UHF radio wave propagation has evolved significantly since the first wireless services began to appear. Over the years, radio planners have had to satisfy the conflicting requirements of accuracy and computational efficiency as effectively as possible given the computational resources of the time.

Given the almost unenumerable parameter space governing UHF propagation over terrain, as well as the massive scale of the problem, simplifying approximations must be made in order to render the computation tractable. As the computational tools become more sophisticated we may relax these constraints. Early techniques relied upon simple formulae [3], geometrical optics with diffraction corrections allow specific topographical information to be included [4], the parabolic approximation to the Helmholtz equation [5] has been used more recently.

The high accuracy of the integral equation (IE) formulation was demonstrated by Hviid *et al*[6], as indeed was its main disadvantage, namely the tremendous computational burden; after all, accuracy and complexity are conflicting features of the same computational aspect. In contrast with GTD and the parabolic equation, the IE formulation is physically exact providing full-wave solutions the only approximations being introduced through the boundary condition.

The work of the Trinity College Dublin propagation group over the last few years has concentrated on the development of efficient IE solution schemes, in an attempt to render feasible the implementation of realistic IE propagation models on a modest computational resource such as a desktop workstation. In this paper we outline three schemes used by ourselves in this regard; the Fast Far Field / Green's Function Perturbation method (FAFFA/GFPM)[7] [8] [9], the Natural Basis Set (NBS)[10][11][12] and the Tabulated Interaction Method (TIM)[13]. The three, seemingly disparate, methods have a common solution strategy which we explore in [1]; they offer dramatic computational savings over standard IE solution methods and render the IE approach practical for application in radio planning. Results are presented which illustrate excellent agreement with published measured data and demonstrate the computational savings.

II. Integral equation formulation for BEM solution

Here we make the further assumption that, when computing the electric field strength above the terrain along a radial starting at the transmitter, the terrain height is invariant in the direction transverse to the radial. If we further assume that the source may be represented by a transverse magnetic line source then our problem becomes scalar and two-dimensional.

To construct the integral equation the terrain heights are taken at regular range intervals, the intervening terrain modelled by a straight line segment. It is important to realise that these assumptions, desirable for the numerical efficiency they facilitate, are by no means necessary and can be relaxed as required by utilising accordingly more sophisticated integral equations than that presented below.

Assuming a TM^z polarised line source with time variation $e^{j\omega t}$ assumed and suppressed we write the 2D Electric Field Integral Equation (EFIE) for a perfectly conducting surface.

$$\frac{\beta\eta}{4}\int_C J(\rho')H_0^{(2)}\left(\beta\left|\rho-\rho'\right|\right)d\rho' = E^i(\rho) \qquad (1)$$

where E^i is the incident electric field, J the unknown surface current, β the radiation wavenumber, η the impedance of the propagation medium (we employ the free space value of 377 ohms). and ρ,ρ' are as indicated in Figure 1.

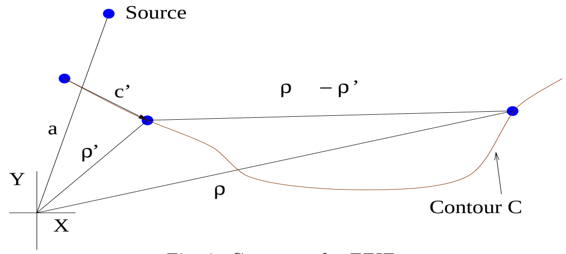

Fig. 1. Geometry for EFIE

The integration contour is along the terrain surface C. To convert the EFIE to a matrix equation we expand J in terms of a set of basis functions

$$J(\rho) = \sum_{n=1}^{N} a_n g_n(\rho) \tag{2}$$

Applying point matching (collocation) at the N points $\rho_1 \ldots \rho_N$ (one on the centre of each basis group) leads to the matrix equation

$$ZJ = V \tag{3}$$

Applying the conceptually simple pulse basis functions with equisized domains of size Δs results in the following system.

$$Z_{mn} = \frac{\beta\eta}{4} H_0^{(2)} \left(\beta \left|\rho_m - \rho_n\right|\right) \Delta s \tag{4}$$

$$Z_{mm} \simeq \Delta s \frac{\beta\eta}{4} \left(1 - j\frac{2}{\pi} \ln\left(\frac{1.781\beta}{4e} \Delta s\right)\right) \tag{5}$$

$$J_n = a_n \tag{6}$$

$$V_m = E^i \left(\rho_m\right) \tag{7}$$

$$\tag{8}$$

The necessity to model accurately the quickly varying phase of J results in a Z matrix of huge size (typically of order 10^5). This matrix cannot be stored let alone inverted. A solution of (3) can still be had,however, by employing an iterative scheme such as 'forward/backward' [14], [15] or a Conjugate Gradient Solver which do not require the explicit storage of the impedance matrix Z but rather calculate elements as required. While tractable, the huge computational times associated relegates these IE solutions to the status of reference solutions for the other, quicker, deterministic models discussed above. Below we outline work performed by ourselves which expedites dramatically these IE methods, rendering them, we feel, feasible deterministic tools in their own right.

III. Three Efficient Solution Schemes

Iterative solutions offer us the potential to solve equation (3) even using simple pulse basis functions though at a considerable $O(N^2)$ computational burden. This is due to the need to perform the sum $\sum_{n=1}^{N} Z_{mn} J_n$ independently for each collocation point ρ_m. To speed up the iterative process we must speed up the matrix-vector multiplies described above. To achieve this we use physical insight to deduce something of the structure of Z from the geometry of the surface under consideration. We omit a detailed explanation of the schemes in this abstract: suffice it to state that the NBS method is very fast but restricted in its application; the FAFFA method is robust (more widely applicable) but slower; and the TIM is both robust and fast.

IV. Results

To illustrate the performanceof the methods referred to in this paper we present numerical computations. There are two examples: the first compares fields predicted by the methods presented versus published measured data collected in Hjorringvej, a gently undulating rural area in northern Denmark [6].

The terrain profile (Fig. **??**) is taken from Northern Denmark and was sampled once every 50m. The transmitting antenna was situated 10.4 metres over the leftmost point and fields were calculated 2.4 metres above the terrain. The chosen frequency was 970MHz, which used 5 pulse basis functions per wavelength, leads to roughly 178,000 unknowns.

Fig. 2 shows excellent agreement between the measured data and (i) a slow $O(N^2)$ reference solution; (ii) a solution using the basic FAFFA with group sizes equal to 50m with the near field restricted to each group's self interaction; (iii)a FAFFA/GFPM hybrid solution using groups 200m in length; (again the near field again was restricted to the group's self-interaction) (iv) a solution obtained using the Natural Basis Set with a domain size of 250m; and finally (v) a TIM solution using groups 50m in size. The table below illustrates the computational savings available with these techniques, with the Natural Basis Set in particular performing extremely well.

The second example involves a more challenging mountainous terrain profile, for which we have no measured data.

Fig. 3 illustrates (i) a slow $O(N^2)$ reference solution; (ii) a solution using the FAFFA with groups equal in size to 5m, and the near field restricted to each group's self interaction; (iii) a FAFFA/GFPM hybrid solution with groups 20m in length;

(The near field again was restricted to the group's self-interaction) (iv) a solution obtained using the Natural Basis Set with a domain size of 1.25m; and finally (v) a TIM solution with a group size of 5m;

We see how the FAFFA and FAFFA/GFPM are in good agreement with the slow reference solution and still offer considerable computational savings (though the physical extent of the groupings had to be much smaller because of the mountainous nature of the terrain). The Natural Basis, while still accurate, is now much slower than the other two fast schemes. This is hardly surprising as it uses one simple phase shift (based on the phase of the incident radiation) to account for scattering from all areas of terrain, ignoring the geometrical considerations inherent in the FAFFA and FAFFA/GFPM. Hence it must use very small groupings to compensate for this inaccuracy with correspondingly slower computation times. This contrasts with the previous example where the flatter terrain produced a greatly reduced spread of angular interaction, a situation exploited to great effect by the Natural Basis. In this example the TIM performs best, giving good agreement with the reference solution.

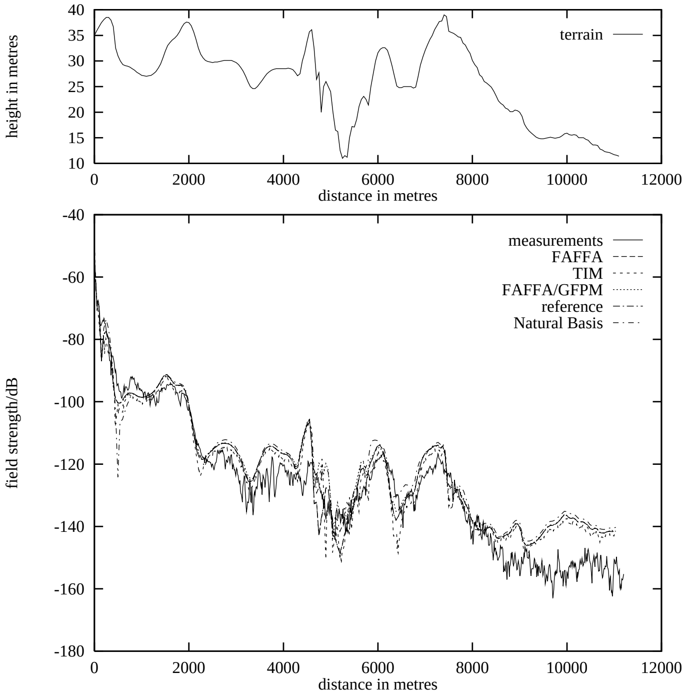

Fig. 2. Hjorringvej terrain profile (sampled at 50m intervals) and fields at 970MHz 2.4m above surface. Line source placed 10.4m above leftmost point. All solutions assumed forward scattering.

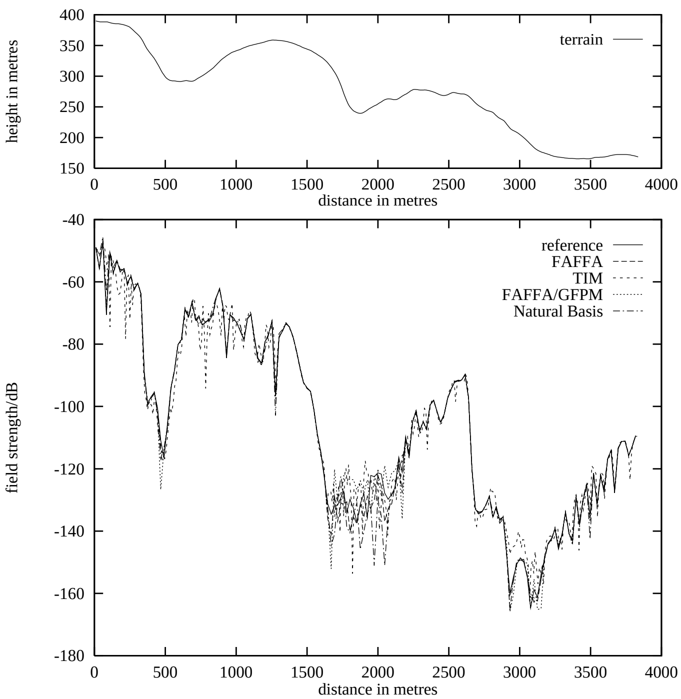

Fig. 3. Mountainous terrain profile, described by 10m segments. Source radiating at 970MHz placed 52.0m above leftmost point and fields calculated 2.4m above terrain surface.

The following table compares computation times (in seconds on a Power PC) between the methods.

Solution scheme	**Hjorringvej**	**Mountainous**
Reference model	100857	12600
FAFFA	120	509
FAFFA/GFPM	50	426
Natural Basis	3	819
TIM	12⋆	49⋆

⋆ These times can be reduced further by a factor of approximately 4 using improvements to the basic TIM scheme. These improvements are outlined in [18].

V. Conclusions and Acknowledgements

Numerical results are presented for three efficient IE methods which show excellent agreement with published measured data. A further numerical study over mountainous terrain illustrated the relative regions of applicability of the schemes.

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