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Comparative Study of Computational Electromagnetics Applied to Radiowave Propagation in Wildfires

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Abstract

In this paper, a comparative study of four computational electromagnetic techniques to model the 2-dimensional radiowave propagation phenomena in wildfires, is proposed. The fire dynamics for a small tree specimen is studied, in which gases released from the combustion process are used to investigate the generation of an ionised plasma and, thus, to evaluate the gradient of the medium refractive index using the cold plasma model. Consequently, the presence of fire has been demonstrated to introduce additional losses in the radio path that may be critical to radio communication systems that are widely used in mission critical applications. The gradient of the refractive index across the vegetation volume yielded by the cold plasma model is used as input parameter to different numerical methods and electromagnetic solvers at 385 MHz (*i.e.* TETRA frequency band in Portugal) and, subsequently, their applicability to wildfires is assessed.

1 Introduction

Every year, around summer time, where temperatures are high and the weather is dry, wildfires seem to devastate wide areas and cause huge damages in different parts of the world. Besides fauna and flora losses, the huge blazes may also affect emergency communication systems, with particular relevance in mission critical applications for fast disaster recovery. Terrestrial Trunked Radio (TETRA) networks used for mission critical operations, typically operate in the frequency bands around 400 MHz [1]. And thus, reliable communication systems are required to ensure the safety of population and help civil protection officials to coordinate the fire brigades [1]. In 2017, the region of Pedrógão Grande in Portugal was affected by deadly wildfires. During this incident, it was detected a failure in the emergency communication system called SIRESP (*Sistema Integrado de Redes de Emergência e Segurança de Portugal*), where people were not able to communicate on radio using mission-critical-push-to-talk services, leading to many lives lost [2]. However, it is not the first report about communication failures in fire environments. Since the 60's decade, fire fighters have testified the radio-wave propagation fragility all around the world, leading to the need to better study, understand and quantify how these wildfires affect such communication networks.

In this paper, the Cold Plasma Model (CPM) is used to characterise the propagation phenomena in a volume of vegetation that is under fire, using a reference scenario of one *Eucalyptus Diversicolor* tree generated in a fire dynamics simulator to provide the required simulation realism. Gradients of the refractive index across the computational volume obtained from the CPM model are then used as input to both numerical and electromagnetic solvers to assess their effectiveness when applied to turbulent media due to fire.

2 Modelling of radiowave propagation in fire

It has been demonstrated in scientific literature that wildfires may affect emergency communication systems [2]. This is due to the formation of an ionised plasma in the vicinity of the flames. A plasma is defined as a gas that presents free ions, electrons and neutral particles [3] and can be generated during vegetation burning. Due to thermal-ionisation, Alkali and Alkali Earth Metals (A-AEM) present in the biomass are dissociated in atoms and, therefore, are ionised to provide ions and electrons [2]. When the plasma is illuminated by an electromagnetic wave, electrons are accelerated by the electric field. Considering that the electron-absorbed energy is transferred to neutrons through elastic collisions, the electrons are scattered isotropically in a way that the average velocity is zero, after the shock. Such absorbed energy is dissipated mainly as heat, causing the wave's electric field to attenuate with distance [2].

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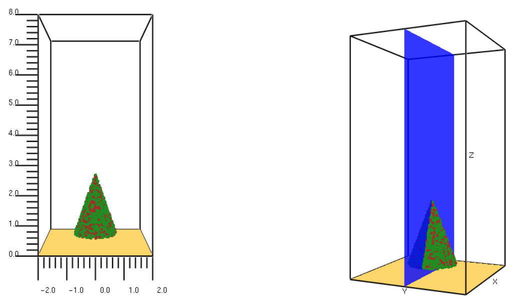
2.1 Fire dynamics

In vegetation media, A-AEM with low ionisation energy is the main responsible source for the formation of electron populations, where the most significant contributions come from Potassium (K), Calcium (Ca) and Magnesium (Mg) that are released during pyrolisis.

A free and open-source computational fluid dynamics software called Fire Dynamics Simulator (FDS) [4], was used to model a fire scenario of a single tree over time. Parameters such as temperature and density profiles of the medium were extracted in order to describe the plasma. The simulated scenario is defined by one *Eucalyptus Diversicolor* tree as depicted in Fig. 1a. Considering the TETRA operation frequency band, a 385 MHz plane wave with normal incidence to the computational volume, and consequently, the plasma, was assumed. For this case, a plasma with A-AEM quantities of K = 0.9%, Ca = 0.82% and Mg = 0.28% was generated to simulate the burning of the tree. The full computational volume of 4x4x8 m^3 was discretised in unit cubic cells of 5x5x5 cm^3, represented by their indices (l,m,n), as depicted in Fig. 2. A full-stack of 80 cubic cells arranged along the direction of propagation represents a propagating tube of 1x80x1 unit-cells, so that the complete vegetation volume can be represented by 161x81 parallel tubes. The scenario was simulated for a duration of 30 s and 3-dimensional profiles of temperature and gases densities were recorded for post-processing.

2.2 Cold plasma model

One way to model the signal attenuation in wildfires is considering the CPM model, in which the critical parameters to calculate attenuation across the fire are electron density and effective collision frequency. Electron density is associated to the free electron population in the plasma and the effective collision frequency indicates the average number of collisions per second, between electrons and other particles. In CPM, the electron density in a plasma environment



(a) (b)

Figure 1. Designed scenario in FDS: (a) example of one tree and (b) plane XZ when Y = 41.

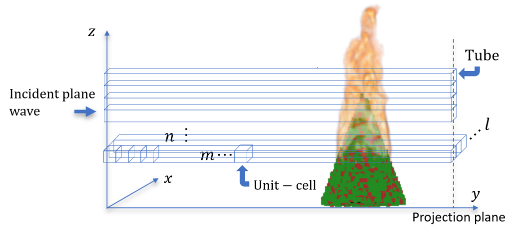


Figure 2. Geometry of the simulation volume.

can be calculated, as presented in [5], by (1):

$$N_e = (K_1 N_a)^{\frac{1}{2}} \left[\left(1 + \frac{K_1}{4N_a}\right)^{\frac{1}{2}} - \left(\frac{K_1}{4N_a}\right)^{\frac{1}{2}} \right] \left[\mathrm{m}^{-3}\right], \quad (1)$$

where K_1 is given by Saha's equation and N_a is the total density of A-AEM particles, atoms and ions in the medium.

Considering that only electron-neutral collisions are the dominant interactions, the effective collision frequency between these particles can be estimated by (2), as in [2]:

$$\nu_{eff} = 7.33 \times 10^3 N_m a^2 \sqrt{T} \left[\mathrm{s}^{-1}\right], \quad (2)$$

where T is the electron temperature (in Kelvin), a is the radius of air element molecules and N_m is the density of air molecules. Contributions from molecules of water vapour (H_2O), carbon dioxide (CO_2), nitrogen (N_2) and oxygen (O_2), were calculated.

This method defines the plasma frequency as $\omega_p^2 = \frac{N_e e^2}{m\varepsilon_0}$ and the complex permittivity of the medium, as shown in (3) [6]:

$$\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 \left[1 + \frac{\omega_P^2}{\omega\left(i\nu_{eff} - \omega\right)} \right]. \quad (3)$$

Both parameters are important to describe the refractive index and the propagation constant, the latter defining the way a wave propagates, based on its phase and amplitude and it can be calculated using (4):

$$\gamma = \alpha + j\beta = j\omega\sqrt{\mu_0 \varepsilon_0 \varepsilon_r}, \quad (4)$$

where α and β are attenuation (in [Np/m]) and phase (in [rad/m]) constants, respectively, μ_0 is the vacuum permeability and ε_0 is the vacuum permittivity.

3 Comparative study of computational electromagnetics

3.1 Methodology

In this section, a comparative analysis between different computational techniques to evaluate the overall excess attenuation due to fire and results convergence, is presented. Results obtained from CPM model are used as input parameters to 4 different approaches, two of which are numerical techniques, namely Full-Stack (FS) and Transmission Line Model (TLM), and the other two are methods of full-wave analysis, i.e. an in-house developed Finite-Difference Time-Domain (FDTD) and the commercial CST electromagnetic transient solver. The dielectric characteristics of each cube (permittivity and conductivity) were extracted from the complex permittivity data obtained by the CPM model. The results (in time domain) were then converted to frequency domain in order to verify whether the S-parameters obtained were in good agreement with those by the other methods.

At first, performance analysis and convergence tests were carried out on individual tubes as an initial benchmark between techniques. Hence, two sets of simulations were carried, based on one and four tubes.

3.2 Full-stack technique

As a first attempt to calculate the overall attenuation on a per-tube basis, a two step-procedure was followed: (i) the individual uni-cell attenuation was evaluated based on the specific refractive index using (4), *i.e.* assuming the cell to be homogeneous, following denormalisation to its physical dimension along y-axis; and (ii) the overall tube attenuation was evaluated using the superposition theorem, in which the cumulative attenuation was obtained by summing the attenuation of each individual uni-cell comprising the tube. This procedure, albeit empirical, is named herein as Full-Stack (FS) technique. For simplicity, no coupling effects or interactions between adjacent tubes were considered. According to analytical results, the maximum attenuation at the plane XZ for $Y = 41$ occurs when the simulation time is equal to 11.2 s, approximately, being this time step the one used for the remaining simulations presented in this paper. Thus, the cumulative attenuation on a per-tube basis using the FS technique at the vegetation-air interface (Y=80) and for a given time step (t = 11.2 s), is presented in Fig. 3. The tube with highest attenuation from the FS results was chosen as the example for the subsequent tests.

Interestingly, from a close analysis of Fig. 3, the effect of fire, as far attenuation is concerned, is mostly visible in

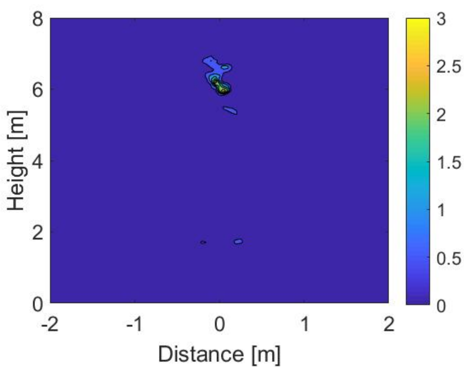


Figure 3. Total attenuation [in dB] on a per-tube analysis using the FS technique, at $t = 11.2$ s.

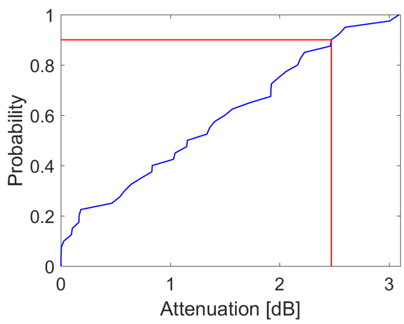


Figure 4. Analysis of ROI (FS).

a small region of the computational volume (and, consequently, in the projection plane), which in fairness is consistent with the peak values of temperature registered during the simulation (burning) period, typically above 1200 K. In any case, it is expected that for a large-scale simulation that mimic real-sized trees, this region of interest (ROI) may be significant expanded. And thus, in order to unbias the results, the statistical analysis of the ROI was limited to a height between 5.9 and 6.35 m and for a width (along x-axis) of -0.05 and 0.1 m. The cumulative distribution function of this particular region is depicted in Fig. 4. It can be seen that for this particular region, 10% of the attenuation values lay between 2.47 and 3.10 dB, which is a remarkable attenuation for such a small ROI.

3.3 Transmission Line Model

TLM is based on impedance matching in multiple dielectric slabs, in which propagation and marching matrices are calculated, so that incident and reflected fields are considered at each unit-cell interface. The overall reflection and transmission responses can be obtained recursively.

The total attenuation in the projection plane for the considered time step and for a frequency of 385 MHz was calculated using the TLM, where very good agreement with that obtained in Fig. 3 using FS was observed. The study of the CDF of the ROI was also performed, yielding a 2.42 dB of peak excess loss for 90% probability of occurrence. This is also in good agreement with the one obtained with the FS model, with a difference of only 0.05 dB, which is considered to be negligible and/or within the model's precision.

3.4 Full-wave analysis

For complete validation and effectiveness of the numerical models used, the simulation volume was tested against simulations obtained from well established electromagnetic tools: an in-house developed FDTD and CST Studio Suite from *Simulia*. The FDTD method is used for solving Maxwell's equations in the time domain [7], allowing a full-wave analysis of the computational volume. Despite the multitude of electromagnetic solvers commercially available, the FDTD method is very demanding if electrically large computational volumes are required. CST Studio Suite was used as this is a well established, accurate and efficient computation tool.

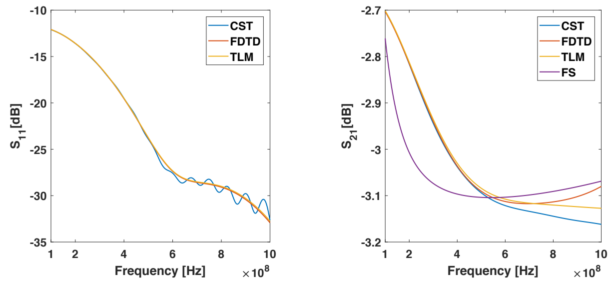
However, limitations were found when simulation of the full computational volume of 161x80x81 unit-cells was considered. This is due to the large memory required to store both geometrical and material information. In particular, for the latter, the refractive index of the proposed volume depicted in Fig. 2 varies from cell-to-cell, amounting to circa 1 million of different materials in the graphical simulation environment. Albeit high performance computers would overcome this limitation, it was decided to develop an in-house FDTD tool built upon the MatLab framework given in [7], so that an all-encompassing simulation tool within the same computational environment could be attained. And, thus, the rationale of developing the FDTD code, having in mind future developments. For completeness, the in-house FDTD tool is validated against CST, using the same geometry and input parameters, as presented below.

3.5 Comparative analysis

For comparative purposes, Figure 5a depicts the S_{11} obtained for one tube only using TLM, FDTD and CST, while Fig. 5b shows the S_{21} parameter for the same scenario, now also including the FS model. It can be seen that good convergence is obtained for the desired frequency band (around 385 MHz). Differences are consistently below 0.1 dB for both S_{11} and S_{21}, which is thought to be within each method's precision, and thus, representing a good agreement for the simulated scenario. A summary of the performance analysis between different methods, in terms of accuracy and computational time, is presented in Table 1. TLM model proves to be the fastest one while proving good accuracy when compared to the in-house FDTD and CST solvers.

4 Conclusions

In this paper, the theory of CPM was used to obtain the complex permittivity across the fire scenario, using mainly the electron density and effective collision frequency. The complex permittivity allowed then to obtain the total attenuation of each tube on a projection plane. A benchmark between different computational methods clearly demonstrated good convergence. The TLM model was found to be the fastest among the tested approaches for evaluation of attenuation in a tube. This makes it potentially interesting for the analysis of large wildfire scenarios. Results obtained in this study clearly indicate that the effect of fire may dictate the reliability of the radio communications in critical mission applications, where excess loss due to fire may well exceed several dB in a real-sized forest environment. Further work will address larger-scale models for varying fuel heaps, wind speeds and directions.



(a) (b)

Figure 5. Comparison of the results for one tube obtained using different methods: (a) S_{11} and (b) S_{21}.

Table 1. Performance analysis.

	Number of tubes	*Method*			
		TLM	CST	FDTD	FS
S11 (dB)	1	-18.95	-18.91	-18.97	N/A
	4	-20.5	-20.65	-20.54	N/A
S21 (dB)	1	-3.019	-3.027	-3.024	-3.094
	4	-2.271	-2.295	-2.278	-2.337
	ROI (90% prob.)	-2.42	N/A	N/A	-2.47
Computational time (s)	1	<6	<30	600	5×10^{-3}

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