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Modelling of Radiowave Propagation Through Small-scale Forest Fire

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Abstract

This paper presents an electrical modelling of radiowave propagation in a fire environment. A small-scale forest represented by 8 *Pinus Pinaster* trees was designed using the Fire Dynamics Simulator (FDS). The excess loss introduced by fire was evaluated using the Cold Plasma Model (CPM) and the Transmission Line Method (TLM), for a 385 MHz plane wave normally incident. Statistical analysis of the estimated overall attenuation is presented, in addition to the minimum and maximum relative permittivity and refractive index values across the measurement volume.

1 Introduction

Widlfires are considered a global environmental problem [1]. Due to their damaging potential, forest fires may result in degradation of biomes, increase of pollution, property destruction and human losses [2]. Recent tragic events as in California, Australia and Portugal show the devastating effects of uncontrolled fires.

Furthermore, it is also known that wildfires may attenuate radiowave signals, specially the ones in Very (VHF) and Ultra High Frequency (UHF) bands. Such occurrences were reported, for instance, during the Dwellingup (1961) and Lara (1969) bushfire disasters in Australia [3].

In order to evaluate the impact of fire on radiowave signals, only a few studies have been performed yet. Hata and Doi, in [4], have presented a propagation test through fire at 40 GHz. Schneider and Hofmann, in [5], have investigated effects of dispersion and absorption phenomena of microwave signals propagating through flames. In [6], Boan *et al.* presented measurement results of broadband radio propagation in a vegetation combustion environment, indicating considerable effects on radiowave propagation, particularly at VHF and UHF frequency bands. Also, Mphale *et al.*, in [7], measured microwave signal losses from 1.6 to 5.8 dB in a controlled pine litter fire.

It is known that the flame itself has minor impact on radiowave propagation [8]. Therefore, the main reason for excess loss introduced by fire is due to the presence of a weakly ionised plasma, generated during vegetation combustion [9]. At high temperatures, the Alkali and Alkaline Earth Metals (A-AEM) present in biomass are dissociated and ionised, generating charged particles that will form a combustion induced plasma. The most significant contributions come from Potassium (K), Calcium (Ca) and Magnesium (Mg) that are released during pyrolisis. When the electromagnetic wave travels through such media, part of its energy is absorbed, leading to wave's electric field amplitude attenuation with distance [3].

In this paper, the effect of a small-scale forest fire on radiowave communication is presented. A simulation with 8 *Pinus Pinaster* trees burning from the bottom, at the same time, was implemented in Fire Dynamics Simulator (FDS), in order to extract the input parameters for the Cold Plasma Model (CPM). Attenuation was then estimated, considering the Transmission Line Method (TLM) [10]. This paper is organised as follows. In section 2, electrical modelling of CPM and its outputs used for computation of attenuation, is presented. Section 3 describes the simulated environment and the overall estimated attenuation. Final considerations are given in section 4.

2 Cold Plasma Electrical Modelling

As a result of its characteristics, the weakly ionised plasma generated in wildfires can be modelled by applying the CPM [9]. In this model, two parameters are essential in order to estimate the excess loss introduced by fire, *i.e.* the electron density and the effective collision frequency. By definition, electron density corresponds to the free electron population in the plasma whereas the effective collision frequency express the average number of collisions per second, between electrons and other particles.

2.1 Electron Density and Effective Collision Frequency

According to Frost [11], electron density $\left(m^{-3}\right)$ can be determined by equation (1)

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

being K_1 given by Saha equation (2) [11]

$$K_1 = 2\frac{g_i}{g_0}\frac{(2\pi m_e kT)^{\frac{3}{2}}}{h^3} e^{-\frac{eV_i}{kT}}, \qquad (2)$$

where, g_i and g_0 are the internal partition function of ions and neutrons, respectively, m_e is the electron mass $(9.109 \times 10^{-31}\ kg)$, k is the Boltzmann constant $(1.381 \times 10^{-23}\ J/K)$, h is the Planck constant $(6.626 \times 10^{-34}\ J \cdot s)$, e is the electron charge $(1.602 \times 10^{-19}\ C)$, T is the absolute temperature and V_i is the ionisation energy.

Still referring to (1), N_a is the total density $\left(m^{-3}\right)$ of A-AEM particles, ions and atoms, defined in equation (3) [11]

$$N_a = n_0 + n_e = 7.335 \times 10^{27} \frac{\xi}{T}, \qquad (3)$$

where n_0 and n_e are the densities per cubic meter of neutral particles and electrons, respectively, ξ is the pressure expressed in atmospheres (atm) applied by the A-AEM at a given temperature T.

When considering only electron-neutral interactions, the effective collision frequency (s^{-1}) between these particles is given by equation (4) [7]

$$\nu_{eff} = 7.33 \times 10^3 N_m a^2 \sqrt{T}, \qquad (4)$$

where N_m is the density of air molecules, a is the radius of air molecules and T is the electron temperature.

2.2 Computation of Attenuation

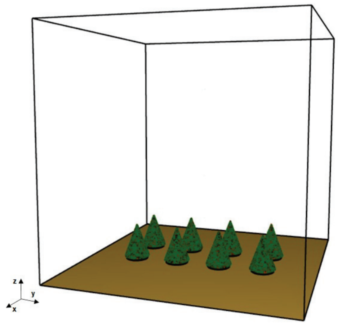
The way a wave propagates in a specific medium is defined by the propagation constant γ $\left(m^{-1}\right)$

$$\gamma = \alpha + j\beta = j\omega\sqrt{\mu_0 \varepsilon_0 \varepsilon_r}, \qquad (5)$$

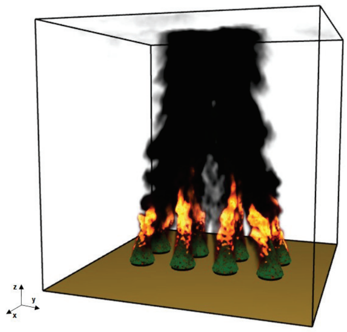
where α and β are the attenuation and phase constants, respectively. The propagation constant can also be defined in terms of the vacuum permeability (μ_0), vacuum permittivity (ε_0) and the relative permittivity of the medium (ε_r).

For this study, relative permittivity values can be calculated based on the plasma frequency $(\omega_p^2 = \frac{N_e e^2}{m_e \varepsilon_0})$ and on the effective collision frequency, as indicated in (6) [9]

$$\varepsilon_r = \left[1 + \frac{\omega_P^2}{\omega\left(i\nu_{eff} - \omega\right)}\right]. \qquad (6)$$



(a)



(b)

Figure 1. Designed scenario in FDS: (a) tree arrangement and (b) tree arrangement set on fire.

3 Analysis and Results

The study presented in this paper follows a two-stage procedure: fire modelling and computation of the overall attenuation.

3.1 Fire Modelling

To generate a real fire environment, it was adopted the FDS, which is a free and open-source computational fluid dynamics software [12].

A small-scale forest fire was simulated, as indicated in Fig. 1, where 8 identical trees aligned in the y-axis direction, divided into two groups of four, was designed to burn at the same time, being the fire initiated by a circular burner placed right underneath the trees. Each tree had 2.25 m height and a diameter of 1.65 m. The total mass of each tree was approximately 5 kg.

For this study, the A-AEM quantities present in the *Pinus Pinaster* trees were considered as K = 0.45%, Ca = 0.25% and Mg = 0.13% [13]. Dimensions of the full computational volume are 16x16x16 m^3, being discretised into unit cubic cells of 8x8x8 cm^3. The total simulation time was 30 s and 3-dimensional profiles of gas densities and temperature were recorded. A 385 MHz plane wave normally incident from the negative y-axis direction was considered.

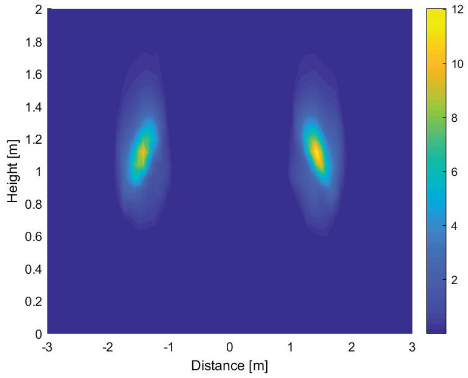


Figure 2. Total attenuation (dB) for t=19.9 s.

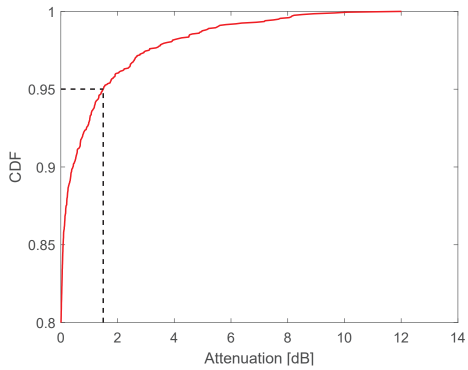


Figure 3. Cumulative distribution function for t=19.9 s.

3.2 Transmission Line Method

To estimate the excess loss introduced by fire, the TLM model was implemented. From this, transmission and reflection coefficients of the propagation path were evaluated on a per-tube basis. It was assumed that each cubic unit cell from FDS simulation presents uniform electrical properties, that vary according to fuel and fire conditions. Hence, based on the relative permittivities calculated in section 2.2, the S_{21} parameter of a transmission line cascade was calculated recursively.

The chosen time instant was t=19.9 s, that corresponds to the instant of maximum attenuation in the projection plane. The projection plane (virtually located at the end of the positive y-axis direction volume) was considered as reference in order to evaluate the overall attenuation. To highlight the regions that most contributes to computation of attenuation, results are shown only for 2 m height and a distance range of 6 m. From Fig. 2, it is possible to observe attenuation values up to 12 dB. These values are seen grouped into two regions, that corresponds to the 2x4 lines of trees. Also, the highest values are between 1 and 1.2 m height, that coincide with the middle height of trees.

The cumulative distribution function (CDF) of this region is depicted in Fig. 3. It can be seen that for this specific time step, 95% of the attenuation values are below 1.5 dB, which are remarkable results when considering that this is small-scale simulation scenario.

As indicated in section 2, attenuation values are closely related to the relative permittivity (ε_r) of the medium. For this scenario, maximum and minimum ε_r and the respective refractive indexes (n) are indicated in table 1.

Table 1. Environment electrical parameters

	Maximum value	**Minimum value**
$\boldsymbol{\varepsilon_r}$	0.9795 - 0.3683i	0.9969 - 0.0557i
n	1.0065 - 0.1830i	0.9988 - 0.0279i

4 Conclusions

In this paper, the effect of a small-scale forest fire on radiowave propagation, is presented. A forest represented by 8 *Pinus Pinaster* trees was designed using the FDS to simulate a real fire environment. From FDS, it was retrieved both temperature and gas densities parameters required for the CPM. The relative permittivities from the weakly ionised plasma generated during vegetation combustion were calculated and used in the TLM to estimate the overall attenuation in the projection plane, for a specific time step, considering a 385 MHz plane wave normally incident. Values of up to 12 dB were found and are considered relevant, since dimensions of the analysed volume are relatively small. The highest values are seen grouped into two regions, that corresponds to the 2x4 lines of trees and are mainly situated between 1 and 1.2 m height, coinciding to the location of vegetation. Finally, future work will address larger-scale analysis and measurements, in which higher values of attenuation are to be expected.

5 Acknowledgements

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