Fire prevention by means of WSN: A preliminary propagation study using Interactive Markovian Agents

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ABSTRACT

Markovian Agent Models are a rather new modeling technique to deal with complex systems composed by a multitude of interacting objects, whose spatial location is also relevant in determining their interaction. A preliminary example of application, which is a part of a larger project, is provided.

Keywords

Fire propagation, Markovian Agents, Wireless Sensor Networks, Performance evaluation.

1. INTRODUCTION

A modern, recent and effective mean for environmental surveillance and protection against various kinds of threats is to resort to a network of autonomous sensors able to collect local information and to transmit them to a sink. Fire is one of the most critical environmental risks throughout the world and surely in all the Mediterranean countries, and fight against fire has become one of the most relevant aspects of environmental protection [1]. Fire prevention may be activated by means of a wireless network of sensors spread randomly in the region to be kept under surveillance. Sensors communicate the stimuli received from the environment to a control station called the sink. Since the sensors need to save power their transmission range is limited and the communication to the sink may occur in a multi-hop fashion.

This is the framework in which our work is positioned. However as a preliminary study to model the behaviour of the WSN network for fire protection, in the present paper, we investigate an analytical model for the propagation of the fire in an inhomogeneous region subject to a non constant wind field. The study is carried out by means of a Markovian Agent *(MA)* model. *MAs* are a relatively new approach [3, 2] to model and analyse very complex systems of interacting objects, where each object has its own local behaviour that can be modified by the mutual interdependencies with the other objects. The spatial location of the objects is retained so that the mutual interdependencies may depend on the relative positions of the interacting objects.

In particular the local behaviour of a *MA* is modeled by a discrete state finite CTMC whose infinitesimal generator may depend on the geographical position of the *MAs*, and the interaction is modeled by allowing each *MA* to send messages that are perceived by the other *MAs*, according to a spatial dependent *perception function*, modifying their behaviour. In a previous work [3] we have shown how the *MA* approach can be utilized to model the transmission of messages to a sink in a grid of identical sensors subject to on-off battery cycles and failures. In [2], we have shown instead how we can exploit the dependency of the *MA* on the local geographical position to model the propagation of an earthquake wave in a inhomogeneous terrain. The aim of the overall project, of which this paper presents the initial stage, is to combine *MAs* of different types, exchanging messages of different nature. To start, we present a preliminary analysis of the propagation of a fire in a region whose burning characteristics depend on the location, and that is subject to a locally varying wind field. The performability measure we propose, is the probability of the fire to reach a given location, surrounding barriers erected to protect a given region.

2. MARKOVIAN AGENT MODEL

For simplicity we choose a two-dimensional square geographical region as shown in Figure 3(a). The region is divided in square cells of equal dimensions such that the burning properties and the wind direction inside each cell can be kept constant as in Figure 4(a). For the fire propagation study we place one *MA* in each cell. The *MA* receives the information on the state of fire from the adjacent cells and transmits its status to the adjacent cells. The total system behaviour is governed by a short range interaction among cells.

A *MA* is an extension of a continuous time Markov chain, that adds the possibility of generating and receiving *messages*. The *MAs* are spread in a geographical region $\mathcal{V}$ and let $\mathbf{v} \in \mathcal{V}$ be a generic location in that region. Let n be the number of discrete states of the *MA* and i ($i = 1 \dots n$) a generic state. A *MA* is characterized by its local infinitesimal generator $\mathbf{Q}(\mathbf{v})$, by the probability of sending messages $\mathbf{G}(\mathbf{v})$ and by a perception function $u(\mathbf{v}', i', \mathbf{v}, i, j)$ that gives the probability that a message generated by an agent in position $\mathbf{v}'$ in state i' is perceived by an agent in position $\mathbf{v}$ in state i and induces a jump to state j.

From the above definitions, we can compute the rate $\beta_i(\mathbf{v})$ at which messages are produced in state i in location $\mathbf{v}$:

$$\beta_i(\mathbf{v}) = \sum_{j \neq i} q_{ij}(\mathbf{v})\, g_{ij}(\mathbf{v}) + \lambda_i g_{ii} \tag{1}$$

where λ_i is the rate of the *self-loop* transitions from state i to itself.

The density of agents in location $\mathbf{v}$ at time τ is denoted by $\boldsymbol{\rho}(\tau, \mathbf{v}) = [\rho_i(\tau, \mathbf{v})]\ i = 1 \dots n$. We call $\gamma_{ij}(\tau, \mathbf{v})$ the rate at which messages are observed by a *MA* in position $\mathbf{v}$, at time τ in state i causing a transition to state j. Due to the density of *MAs* in position $\mathbf{v}'$, we have for $i \neq j$:

$$\gamma_{ij}(\tau, \mathbf{v}) = \int_{\mathcal{V}} \sum_{i'=1}^{n} \rho_{i'}(\tau, \mathbf{v}') u(\mathbf{v}', i', \mathbf{v}, i, j) \beta_{i'}(\mathbf{v}') d\mathbf{v}' \tag{2}$$

and we set:

$$\gamma_{ii}(\tau, \mathbf{v}) = - \sum_{j \neq i} \gamma_{ij}(\tau, \mathbf{v}) \tag{3}$$

Let matrix $\Gamma(\tau, \mathbf{v}) = [\gamma_{ij}(\tau, \mathbf{v})]$ collect the rates computed from (2). The actual transition rate matrix $\mathbf{C}(\tau, \mathbf{v})$ that characterizes the stochastic process of a *MA* at position $\mathbf{v}$ and time τ, is composed by a local term $\mathbf{Q}(\mathbf{v})$ and an interaction induced term $\Gamma(\tau, \mathbf{v})$ as in the following equation.

$$\mathbf{C}(\tau, \mathbf{v}) = \mathbf{Q}(\mathbf{v}) + \Gamma(\tau, \mathbf{v}) \tag{4}$$

Defining from Equation (4) a matrix $\mathbf{C}(\tau, \mathbf{v}) = [c_{ij}(\tau, \mathbf{v})]$, the state density vector of each *MA* can be obtained by solving the standard Chapman-Kolmogorov equation:

$$\frac{d\rho_i(\tau, \mathbf{v})}{d\tau} = \rho_i(\tau, \mathbf{v})\, \mathbf{C}(\tau, \mathbf{v}) \tag{5}$$

Equations (5) is solved analytically by an iterative numerical procedure starting from a known initial condition $\rho(0, \mathbf{v})$.

3. FIRE PROPAGATION MODEL

We will address the study of outdoor flame propagation in a (two-dimensional) region $\mathcal{V}$, in particular in presence of grass or bushes in the environment. The dynamic of this phenomenon strongly depends both on the wind direction and intensity and the type of materials being incenerited. The work in [1] shows that flames roughly spread following an expanding ellipse where the origin of the fire is placed on one of the focus whereas the other focus moves along the major axis of the ellipse according to the fire-front speed as shown in Figure 1. Both the eccentricity of the ellipse ϵ and the fire-front speed r_w depend on the environment wind speed W. We assume that they are related by the following equation:

$$r_w = r_0(1 + c_f W) \tag{6}$$

where r_0 represents the Rate of Spread (ROS) of the fire in absence of wind and take the value $0.165\, m/s$ and c_f is a coefficient relating wind speed to ROS [4]. Given the value of the fire-front speed r_w and the ROS r_0 the eccentricity of the resulting expanding ellipse can be determined as:

$$\epsilon = \frac{r_w^2 - r_0^2}{r_w^2 + r_0^2} \tag{7}$$

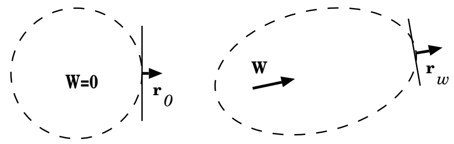

Figure 1: Elliptic Propagation.

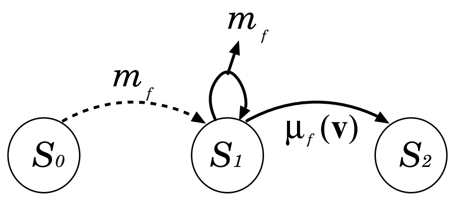

Figure 2: Fire Propagation Agent.

We model the fire condition in a cell of the grid by a *MA* with three states (Figure 2). State S_0 is the situation of non-burning, state S_1 the situation of burning and state S_2 the extinguishing of the fire after burning. Each local transition is represented by a solid arrow and it is labelled with the corresponding transition rate. Induced transitions are represented with dashed arcs and are labelled with the message whose perception induces the transition. Initially the agent is in state S_0 meaning that it is not burning, however the reception of a fire message m_f from adjacent cells induces a transition to the burning state S_1. In state S_1, the message m_f is broadcast to the adjacent cells at a constant rate λ_f. The last transition to the absorbing state S_2 indicates the extinguish of the fire in the cell; the rate μ_f is the extinguishing rate.

To model the elliptic propagation of fire, the perception function u is defined as:

$$u_{m_f}(\mathbf{v}', s_{i'}, \mathbf{v}, s_i, s_j) \;=\; \begin{cases} 1 & \text{if } (|\mathbf{v}' - \mathbf{v}| < R) \wedge \\ & (s_i = S_0) \wedge (s_j = S_1) \\ 0 & \text{otherwise} \end{cases}$$

where:

$$R = \frac{a(1 - \epsilon^2)}{1 - \epsilon\, Cos(\theta - \alpha)} \tag{8}$$

is the equation in polar coordinates (R, θ) of an ellipse with semi-major axis length a, eccentricity ϵ rotated by an angle α. Given this definition, a receiving agent in position $\mathbf{v}$ perceives fire messages only when it belongs to an elliptic area centered on the position $\mathbf{v}'$ of the sender agent. The eccentricity ϵ depends on the wind speed W and can be determined by Equation (6) and (7); the rotation angle α depends on the direction of the wind vector.

3.1 Environment model

The ability of the model to correctly reproduce the fire propagation in the environment, is closely related to the spatial parameters of the agents. We imagine to be able to extrapolate the required parameters from appropriate charts. For example, we suppose that the characteristic of the terrain can be computed automatically from a satellite image like the one presented in Figure 3(a) using image processing techniques. With similar approaches, we suppose being able to compute also the fire-extinction rate $\mu_f(\mathbf{v})$. For what concerns the wind, we imagine to have several meteorological stations capable of measuring both the wind speed and the wind direction, and to interpolate their value to produce wind map similar to the one presented in Figure 4(a).

4. NUMERICAL RESULTS

We have developed a simple application in *Adobe Flash*, that extracts the agent densities and the fire-extinction rate form the RGB channels of a satellite image, and that allows the user to specify the wind direction sampled by the meteorological stations.

We have analysed the dynamic behaviour of the fire propagation in variable environment conditions over a 32×32 grid of cells (about $1.5 - 2\ Km^2$), solving the differential Equations (5) using the implicit Euler technique with a time discretization step $\Delta t = 0.01 min$. We assume that in each cell resides at most a single agent. All the numerical computations takes as few minutes to be completed. We plot the two-dimensional spatial density of agent in the burning state $\rho(\mathbf{v}, S_1)$. Darker points in the grid correspond to low values of density of burning agents, lighter points to high value.

In the first set of experiments, we study the effect of both the wind speed and direction on the fire propagation. We analyse two scenarios: in the first we assume that the fire originates in the middle of the left edge of the area in Figure 3(a) where the wind blows with a constant direction from west to east and with a constant speed; in the second we assume that the fire starts at the bottom left corner of the map and the wind follows the vector field shown in Figure 4(a). In both cases we plot the results at the time instants $t = 40, 60, 90 min$. When the wind is constant, Figure 3 shows, as expected, that the resulting fire propagation is an expanding ellipse moving according to the wind direction. When the wind direction varies, the ellipse can be recognized only in the first instants of the propagation, then it changes in a less regular shape due to the effect of the wind. Notice that the mean intensity of the wind vector is higher in the variable wind scenario than the constant one, resulting in a faster propagation.

Firebreaks are a typical method used in the fire prevention techniques which consists in a gap in the vegetation that slows down or stops a spreading wildfire. In our model this can be accounted through the initial spatial agent density $\rho(0, \mathbf{v})$, therefore in the second set of experiments, we study the effect of this parameter. We consider two cases: a long firebreak that crosses the whole map(Figure 5(a)) and a shorter one(Figure 6(a)). In both cases the fire starts at the middle left edge of the map, the wind is constant and we plot the results at the time instants $t = 50, 60, 70 min$. Results are shown in Figure 5 and 6, respectively. In the first case, it is clearly shown how the long firebreak completely prevents the fire to propagate further. Notice also that the fire front persists along the firebreak even after $70 min$ from the starting of the wildfire, meaning that the firebreak prevents the fire spreading, but it does not decrease the extinction time. In the second case a similar behavior can be recognized, however the fire gets around the firebreak due to its short extension.

5. CONCLUSIONS AND FUTURE WORK

In this paper we have presented a preliminary work to study wildfire propagation in a region. Starting from a simplified elliptic model of the fire spreading, we develop a MAs based model which accounts for spatial variable burning characteristics of the terrain and locally varying wind field. We plan to integrate this work with the model of wireless sensor network presented in [3]. The integrated model will include two type of messages: one representing the fire spreading, the other representing a fire alarm sent by a sensor to a control station that starts an evacuation plan. The aim of the project is to model a wireless sensor network possible degraded due to burning of its node and to calculated a performability measure such as the probability that an evacuation alarm is sent on time before controlled buildings are reached by the fire.

Acknowledgments

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6. REFERENCES

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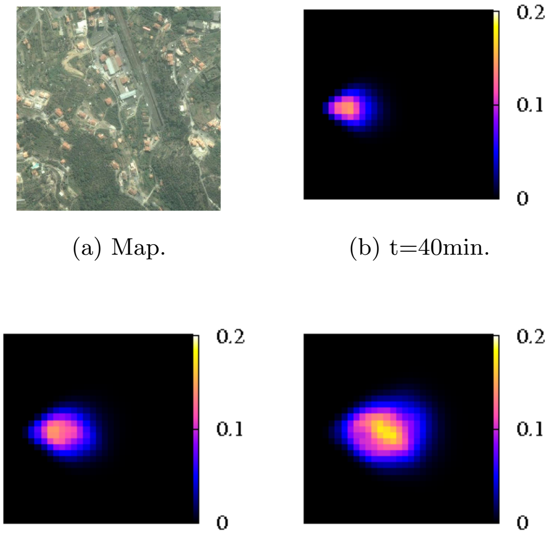
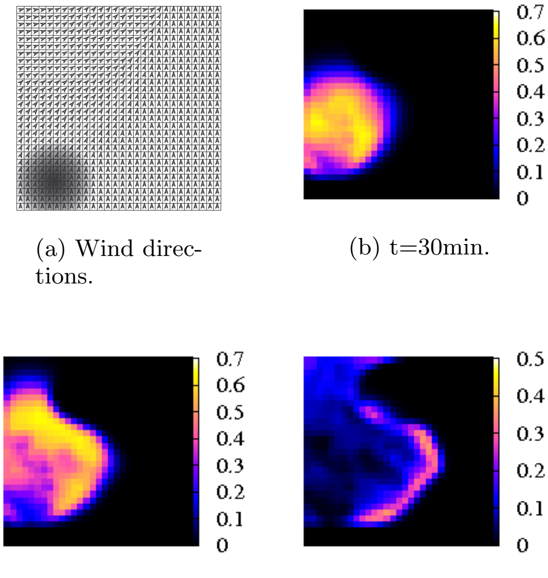


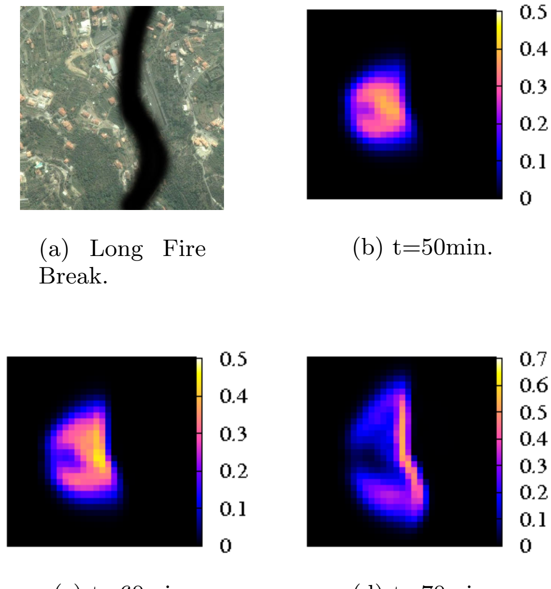
(a) Map. (b) t=40min. (c) t=60min. (d) t=90min.

Figure 3: Fire Propagation with a constant wind



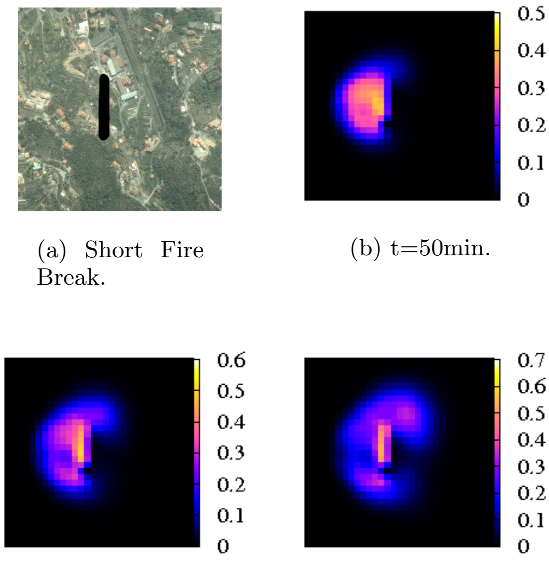
(a) Wind directions. (b) t=30min. (c) t=40min. (d) t=90min.

Figure 4: Fire Propagation with a spatial dependent wind



(a) Long Fire Break. (b) t=50min. (c) t=60min. (d) t=70min.

Figure 5: Fire Propagation in presence of a long fire break



(a) Short Fire Break. (b) t=50min. (c) t=60min. (d) t=70min.

Figure 6: Fire Propagation in presence of a short fire break