A comparative study of two alternative wildfire models, with applications to WSN topology control

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Abstract

In this paper two wildfire modelling methods are compared in terms of performance, scaling up flexibility and speed of model execution. The InteSys model is based on Cellular Automata (CA). Simple rules are applied to each cell, interacting with neighbouring cells. The cell based structure reflects the object oriented nature of the model, as each cell is a working copy of a cell class – a blueprint that enables easy expansion, taking into account undergrowth, tree spacing, moisture content, air temperature, solar radiation, wind velocity, terrain gradient, tree flammability, and other parameters. The CD-AUTH model is based on the Cell-DEVS technique operating also on a domain discretized to interacting cells, incorporating the same as above physical properties, variable in time and coupled to a low level surface wind module. The model applies the Rothermel approach with respect to the fire propagation considering the Huygens ellipse of propagation. Advantages and disadvantages of the two models are discussed on the basis of comparative simulations over hypothetical fire scenarios on a digital map. Important observations and conclusions are also drawn concerning the deployment of wireless sensor networks (WSN) for wildfire detection. Finally, a network topology control algorithm that utilizes the fire prediction algorithms is presented and yields energy efficiency of the WSN, providing with high time resolution data for real time monitoring.

Keywords: wild fire modelling techniques, cellular automata, discrete event simulations, cell-DEVS, wireless sensor networks WSNs, network topology control, energy efficiency WSNs.

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1 Introduction

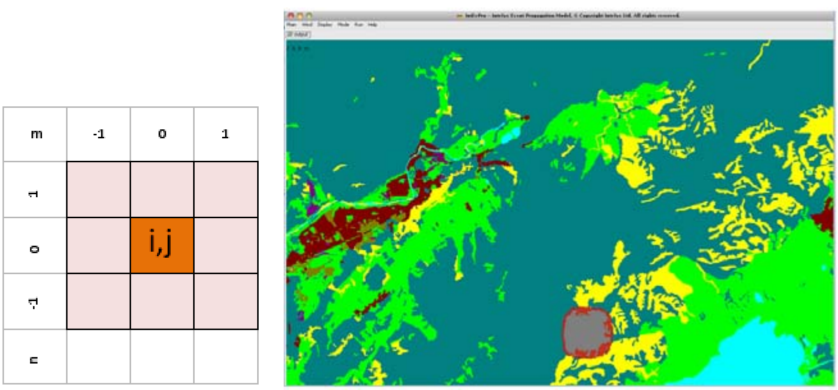
Forest fires detection holds an important role in fire management and different detection strategies have been applied to monitor large areas. These can be automatic video surveillance systems, Unmanned Aerial Vehicles (UAV), satellite imagery and wireless sensor networks (WSN) [1]. The estimation of the risk of ignition of a wildfire in forests is the first step to fire management. That risk is quantified according to the fuel available and the weather conditions via the algorithm of the FWI (Fire Weather Index), established in Canada [2]. Wireless sensor networks are considered as a scalable solution that can provide real time fire detection and monitoring of the crucial parameters of FWI, overcoming limitations of the above mentioned alternative detection techniques [1]. In [3–5], various forest fire detection techniques that are based on the WSNs are presented. Furthermore, WSNs can provide real time measurements of critical parameters to the fire propagation algorithms and this can yield accuracy improvements of the models and better fire predictions and management.

An effective strategy to manage wildfires is based on the detection system used and the algorithm implemented to model the fire propagation in the area of investigation. In general, three alternative modelling techniques exist, namely the empirical, semi-empirical and physical [6]. Semi-empirical models are preferred for engineering application since they produce accurate results with low CPU demands. Rothermel [7] first described fire spread as a mathematical model. Software tools and semi-empirical models are now based on the integration of the Rothermel's equation integrated with cellular automata (CA) or discrete event (cell-DEV) approximation to model the fire spread over digital elevation maps and GIS and are considered as the most suitable approximations. Cellular models of fire growth use fixed distances between regularly spaced grid cells to solve the fire arrival time from one cell to another. There are several types of CA models for fire growth, including the transfer of fractional burnt area, probability driven models and fractal models [8-11]. DEVS are applied to define arbitrary ordinary differential equations. A system model of DEVS is described as a hierarchical composition of submodels each of them being behavioural or structural. Cell-DEVS formalism is a combination of DEVS and CA [12, 13].

In this paper two wildfire modelling methods are compared in terms of performance, scaling up flexibility and speed of model execution. The Intesys model is based on CA approximation being probabilistic in nature with low CPU demands whereas the CD-AUTH model is based on cell-DEVS approximation taking into account the main parameters affecting fire spread from Rothermel's equation and it is coupled to a low level surface wind module for increased accuracy. Consequently, this model has higher CPU demands. An algorithm that enables the use of fire predictions models to WSN topology control is also presented. The fire model is used to predict the growth of fire and feedback the network to provide increased FWI sampling at specific locations, necessary for high resolution in time information to fire fighters and fire management. For the purpose of our investigation the CD-AUTH model was utilized.

2 InteSys-model

The InteSys Event Propagation Model is based on cellular automata machines. Simple rules are applied to each cell, with an interaction framework that operates between neighbouring cells. The system model is not explicitly programmed but it emerges from the component models and their interaction. The cells have geographic connotation and correspond to a raster grid of predefined size, with square cells typically between 10m and 100m sides. The cell based structure reflects the object oriented nature of the model, where each cell is a working copy of a cell class – a blueprint that enables easy expansion of model capabilities, taking into account undergrowth, tree spacing, moisture content, air temperature, solar radiation, wind velocity, terrain gradient, tree flammability, and other parameters. The working copies of the cell class are instantiated at the start of the simulation, and private values of variables in each instance are created either from a GIS data input or from a command file. For each cell, the model employs Moore neighbourhood of 8 cells to perform calculations and derive the status of each cell (Figure 1a)).



a) b)

Figure 1: a) A land cell in position (i, j) in a Moore neighbourhood of 8 cells, b) IntEvPro in operation: after importing an external GIS file and setting relevant parameters, the model simulates the spread of fire in the forest (dark blue cells) and in open areas (yellow cells). The fire is shown as an expanding circular front in the lower end of the centre of the screen. The simulation time, corresponding to the real time, is shown in the upper left corner.

Wind direction is detected in one of 8 compass directions that correspond to the geometric relationship between the cell and its neighbourhood. For instance, wind from south west comes from the lower left corner of the neighbourhood, from position i-1, j-1. Direction is calculated as d=10*m+n (fig. 1a), which gives 8 unique numbers, avoiding duplication in direction references. Response to wind and slope is calculated using Rothermel's equation (2).

Fire ignition: Cells are ignited either randomly, or manually using the pointing device, or using a built in preset location.

Fire propagation through the cell: As fire propagates differently in different cell types, each time a cell is ignited, a burning counter starts and compares its total with a number that corresponds to the burnt down state of that cell type. The slope and wind coefficients reduce the counter's total and thus modify the rate of fire propagation in the cell.

Fire propagation between cells: Neighbouring cells catch fire from burning cells with a certain probability, representing a resistance of fire transfer from one cell to another. This probability is modified using slope and wind related propagation coefficients.

Figure 1b) shows the model in operation using an external GIS file with cell size of 20 m x 20 m, and representing the total area size of 25.7 x 17.6 km. The GIS map that represents the cell types if the main output screen, whilst the map with cell altitudes is used for background calculation of fire propagation parameters.

3 CD-AUTH model

3.1 Model description

CD-AUTH is based on the Rothermel's equations [7], for the description of the fire physics i.e. the thermal energy balance along the propagating fire front, its generation on a burning area and its distribution to fractions of vertically convected energy, radiated energy and energy consumed for the combustion of the adjacent fuel. In order to tackle the spatiotemporal variability of the fire evolution over a realistic topography, due to variable fuel loads, humidity, ground slope, wind intensity and direction etc, the model follows the formalism and algorithmic structure deriving from the timed Cell-DEVS methods [11, 12]. The fire domain is discretized in square cells (Figure 2a)) characterized by pertinent state parameters. The fire is introduced initially at a pre-determined cell and the evolution over the 2D domain is controlled by transitions processes in each cell and between adjacent cells. In each cell of the considered 'cellular automaton', a discrete event simulation is applied, and the system is composed of a large number of interacting individual cells (following a strict procedure), controlled by time delays. The magnitudes produced by Rothermel's equations, are the rate of fire spread, and the fireline intensity (deducing the transition from ground fire to crown fire). These equations are applied locally as a 1D model over the area of one cell.

The model makes use of the Huygen's principle [11] locally, using the geometry of the elliptically extending fire front, having as focus the cell centre and dimensions of the ellipse depending on the superimposed local wind and ground slope magnitudes (Figure 2b)). That principle is used to convert in a controlled manner from the one dimensional cell domain (a cell over which the main direction and the maximum rate of fire spread is calculated by Rothermel' equations), to the two dimensional topography of the burning wildland.

The model receives as input the individual cell fuel properties, the topographic data for the estimation of the ground slope, and the local wind speed and direction. The fuel properties and the wind data can be varying in time, to incorporate scenarios of rain or fire combating from the air, as well as any change of wind direction and intensity.

From the above data the "effective" fire direction and maximum propagation rates are computed as well as the 2D rate of spread along the 8 main compass directions connecting each cell with the adjacent cells, according to the preferred square grid discretization (dx of Figure 1a)). Each cell is characterised by an index specifying the transition of state between a non burning (index=0), a burning (index=1) and a burnt (index=2) cell.

According to the composed algorithm, during each time step the following checks are done over the fire domain

1. check for any variation of the cell state variables
2. check for the spread of the fire from any burning cell to the neighbouring cells
3. check for the consumption of the available fuel in a burning cell.

Mathematically, the CD-AUTH model is defined as:

$$CD - AUTH = < K, X, S, G, t, I, E > \tag{1}$$

where K is the set of points with coordinates, i, j in the region of interest (Figure 2a)), X is the geometrical pattern of the cells and defines the change in the state of (Figure. 2b)), S is the state of the cells set that incorporates values representing altitude, fuel characteristics, fire duration, wind direction, wind speed, fire spread. G is the set of global variables that affects the transition functions of the cells and incorporates values such as weather conditions, wind direction and speed, fuel apothem of the cell, t is the transition function set for surface and crown fire spread according to fuel apothem and wind characteristics, I is the ignition cell, E is the external function set.

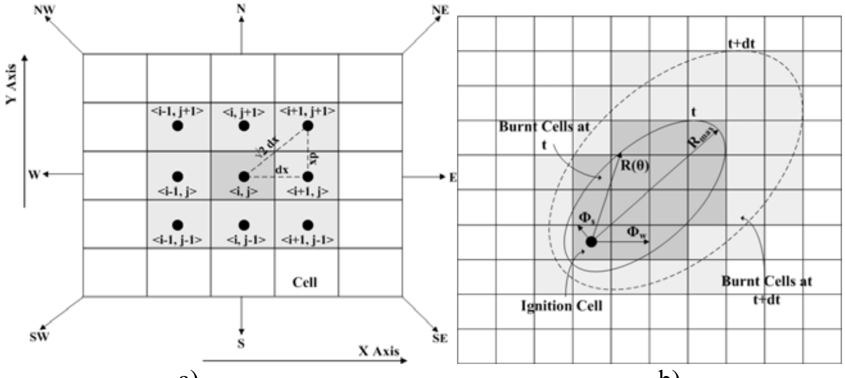


Figure 2: a) Grid of cells in the area of interest, b) Elliptical growth at different time steps.

3.2 Surface fire

The fire spread rate is computed according to

$$R = ROS \cdot (1 + \Phi_s + \Phi_w) \tag{2}$$

where

$$ROS = \frac{I_R \cdot \xi}{\rho_b \cdot h \cdot Q_{ig}}$$
$$\Phi_s = a_s \beta^{-b_s} (\tan\phi)^2 \tag{3}$$
$$\Phi_w = C(a_w U)^B (\beta / \beta_{op})^{-E}$$

In the above equations R is the computed rate of spread, I_R is the reaction intensity, ξ is the propagation flux ratio, ρ_b is the ovendry bulk density, h is the effective heating number, Q_{ig} is the heat of preignition, β is the packing ratio, β_{op} is the optimum packing ratio, φ is the terrain slope [14]. Φ_s, Φ_w represent the terrain slope and wind effects to rate of spread. The parameters incorporated in these equations can be found in [7]. The combined terrain and wind effects are computed according to $\vec{\Phi} = \vec{\Phi}_s + \vec{\Phi}_w$

The fireline intensity is computed according to

$$I_b = q \cdot w \cdot R \tag{4}$$

where q represents the net heat produced and w the weight of the fuel per unit area burned in the flaming front [9]. In an arbitrary direction, the spread rate is computed according to an elliptical model, similar to Huygens approximation, and the fire origin is assumed to be on one of the foci (Figure 2b)) according to $R(\theta) = R \cdot (1-\varepsilon)/(1-\varepsilon \cdot \cos\theta)$ and the eccentricity of the ellipse is given by $\varepsilon = \sqrt{l_w^{\,2} - 1}/l_w$. Parameter l_w is the semi-major over the semi-minor ellipse ratio and depends on the effective midflame windspeed U_{eff} that considers the wind and slope effects according to (3). It is given by

$$l_w = 1 + l_x(e^{a_x U_{eff}} - 1) + l_y(e^{-a_y U_{eff}} - 1) \tag{5}$$

where l_x, l_y, a_y, a_x are constant values obtained by the Anderson's empirical formulations [14].

3.3 Crown fire

The crown fire effect becomes important if the surface fireline intensity I_b presented in (4) is greater than a threshold value I_0 [11, 14]. The crown fire spread rate is computed according to (6). Parameters c_c and d_c are constant with time [14].

$$R_c(\theta) = \mathrm{R}(\theta)\left[1 + \mathrm{c_c}\left(1 - \mathrm{e}^{-\mathrm{d_c}\frac{\mathrm{I_b} - \mathrm{I_0}}{\mathrm{I_b}}\mathrm{R}(\theta)}\right)\right] \tag{6}$$

3.4 Low level surface wind module

The wind over an irregular terrain is affected by the obstructions imposed by the hills and mountains of the scenario. In most cases, the input parameters to (1) concerning the wind speed and direction are extracted by sparse meteorological stations or are assumed homogeneous in all the investigated scenarios. In the CD-AUTH model a deterministic low level wind model (LLWM) is coupled to provide a high resolution wind characteristic at each cell. A numerical solution by an explicit centered first order finite difference scheme on the staggered grid (Figure 2a)) was used. The LLWM is defined by the set of equations

$$\begin{aligned} \frac{Du}{Dt} &= -g\frac{\partial \zeta}{\partial \mathrm{x}} + N\nabla^2 u - \frac{C_b}{h}u\sqrt{u^2+v^2} \\ \frac{Dv}{Dt} &= -g\frac{\partial \zeta}{\partial \mathrm{y}} + N\nabla^2 v - \frac{C_b}{h}v\sqrt{u^2+v^2} \\ \frac{\partial \zeta}{\partial \mathrm{t}} &+ \frac{\partial h}{\partial \mathrm{x}} + \frac{\partial h}{\partial \mathrm{y}} = 0 \end{aligned} \tag{7}$$

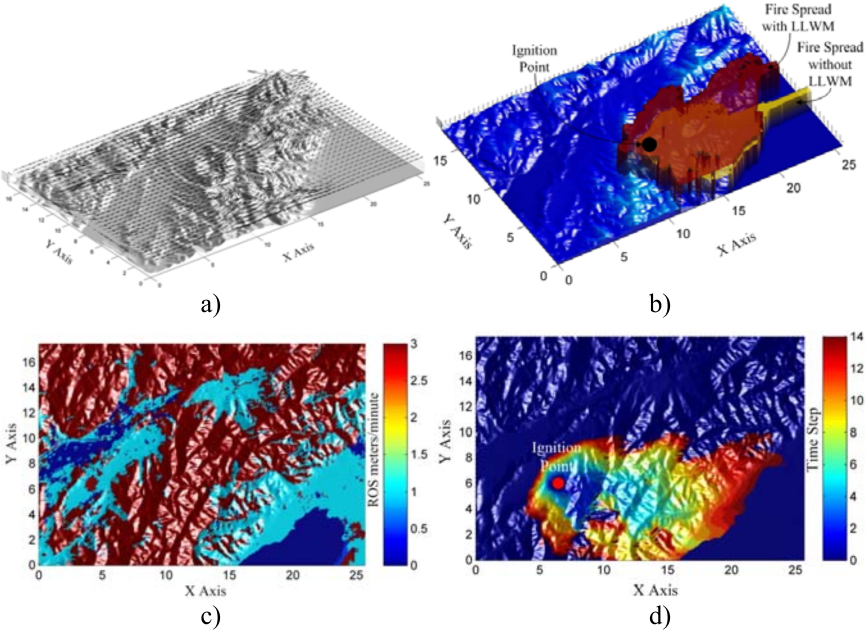


Figure 3: a) Wind vectors of the LLWM for west wind (coming from the left) of 20knt over the terrain, b) Comparison of fire spread, of CD-AUTH model, after time *t* assuming the LLWM and homogeneous wind c) The terrain and fuel characteristics used. d) CD-AUTH fire spread for different time steps coupled with LLWM.

In the above formulation *N* represents the eddy viscosity variable, C_b the surface friction coefficient, *u, v* the mean over the considered layer wind speed components in X and Y direction respectively, h the thickness of the atmospheric layer, defined by the minimum and maximum height of the terrain map and ζ the barometric pressure head distribution. The fire model is coupled with the wind 2DH boundary layer model, producing over the real topography the variable in intensity and direction wind field (its output is the wind speed and direction on every cell), enhancing the effects of ground relief. The model output comprises time sequences of the “cells’ indices” matrix, allowing a subsequent estimation of the evolution of the fire front and the computation of rate of change of the burning and burnt areas during the fire event. The results of the LLWM are shown in Figure 3a) whereas in Figure 3b) the effect of taking into account the LLWM instead of homogenous wind to fire propagation is presented. The firespread for different time steps of the CD-AUTH model is presented in Figure 3 c) and d).

4 Comparison of the models

This section of the paper presents the comparison of the two models. For the purpose of our investigation 4 different time steps was chosen and these are represented by 10, 24, 36 and 48 hours after fire ignition. The simulation results are presented in Figure 4. The comparison represents the subtraction of the burnt

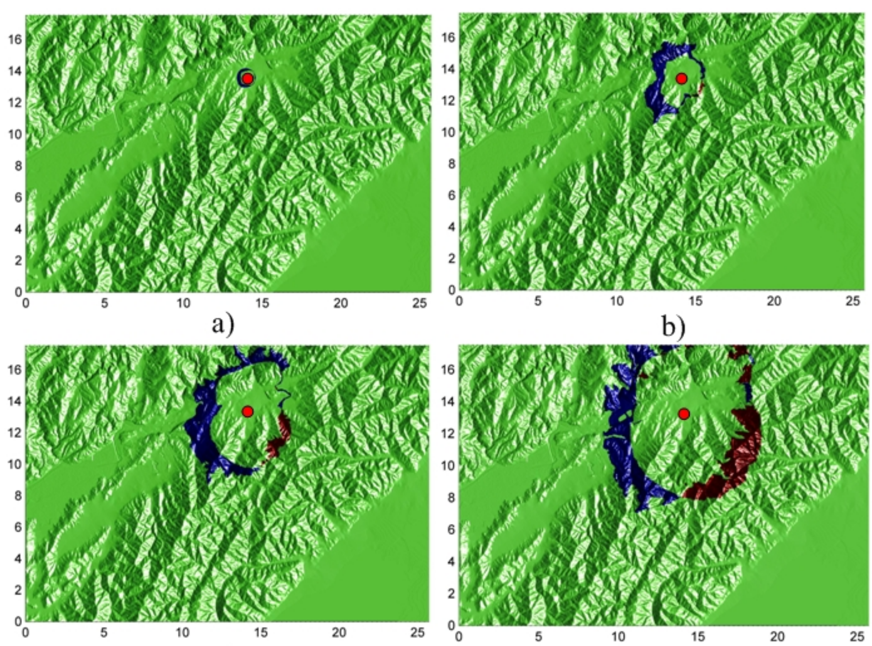


Figure 4: a) comparison for 10 hours after ignition, b) comparison for 24 hours after ignition, c) comparison for 36 hours after ignition, d) comparison for 48 hours after ignition. The red point represents the ignition point.

area computed by the Intesys model and the burnt area computed by the CD-AUTH model. As a result, the blue and red areas indicate the areas where the Intesys model predicted a faster fire line and delayed fire line respectively. It can be observed that the two models are in good agreement at the time step of 10 hours. This is because the fire spreads over a flat terrain and the predictions are mainly characterized by the fuel characteristics. On the other hand at greater time steps there is a small difference between the models and this is mainly caused to the modelling approximations and the shard terrain. In general, a good agreement is observed that is acceptable for fire predictions and management. The CPU demands of the two modelling approximation is identical but the CD-AUTH model presented higher demands when the low level wind module was introduced. This is because the solution of equation (7) in a numerical approximation requires high computation time.

5 WSN network topology control

Wireless sensor networks have been deployed for forest fire detection and monitoring. Furthermore, real time data sent by the sensor network is of vital importance to the fire management and improvement of the fire propagation models. WSNs usually provide weather characteristics that are related to FWI such as temperature, wind, humidity. These data are necessary for fire detection or monitoring of high risk locations. The time resolution that sensors send information to the manager varies according to weather characteristics. In case of low fire risk weather the sensors are set to idle mode in order to save energy whereas at high risk periods the sensors can send information every 15-30 minutes for early fire detection. This condition consumes considerable power and reduces the lifetime of the system. The sensors of the network are powered by a battery and energy efficiency is of vital importance. In [1, 15-16] energy saving techniques are presented based on routing and protocol implementations to wireless sensor networks. For the purpose of our investigation a WSN network topology control is developed that targets lifetime maximization. In case of a fire event, the CD-AUTH model is applied for fire spread predictions and this information feeds the sensor network to self manage and provide multi-time-resolution data of FWI to the fire manager. The proposed algorithm increases the sampling rate at the sensors that are placed on a zone of time T (Figure 5a)) around the current firefront without affecting the sampling rate of the rest sensors of the network. With this approach, fire managers are able to monitor in real time and with frequently updated data the fire event without wasting the total network energy. The goal is that sensors that are expected to be burned by the fire after time T are set to high, almost real time, sampling rates whereas the rest of the sensors monitor the area with the normal set values, providing energy efficiency. The algorithm implements the communication protocol presented in [16]. The power consumed for transmitting and receiving a message with r (bits/sec) over a distance d (m) is equal to

$$P_T(d) = (a_{11} + a_2 \cdot d^{\gamma}) \cdot r \quad P_R(d) = a_{12} \cdot r \tag{8}$$

Parameters a_{11}, a_2 are the transmitter electronic equipments (computational costs) and radio amplifier energy (communication costs) respectively. a_{12} represents the receiver electronic equipments and depends only on the computation processing. Parameter γ is the path loss exponent and depends on the communication link between each sensor and is usually set to 2 or 4. For the purpose of our investigation it was assumed that the sensors are separated by a space d=70m and γ=4. Parameter $a_{11}= a_{12}=$ 50nJ/bit and a_2=0.0013pJ/bit/m^4 [16]. Two scenarios are compared. According to the first, in the case of a fire event the total network increases the bitrate from *Q bits/sec* to *W=3Q bits/sec* and is named as *P*. The second scenario concerns the implementation of the proposed topology control where the sensors placed in the area of interest (firefront after time T) increase their sampling rate and is denoted as P_{NC}.

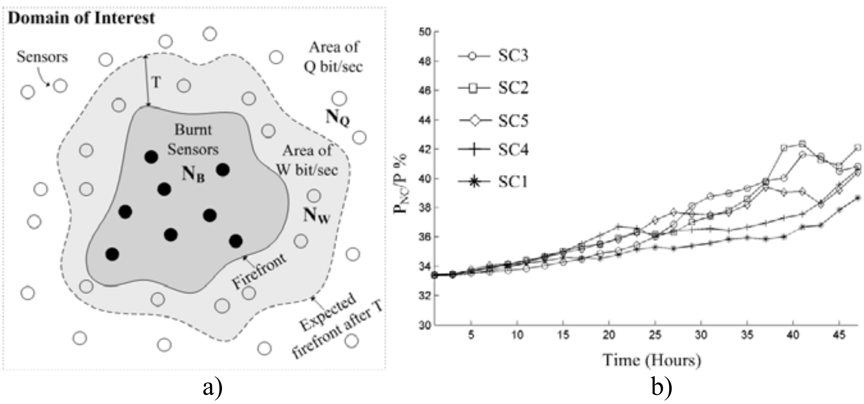


Figure 5: a) Interpretation of network topology algorithm. b) Power gain for 5 different fire scenarios over a period of 2 days after fire ignition.

An area of 5x5 Km was examined with total number of sensors N_T*=5100*. The total network power consumption for the two cases is computed according to

$$P = \sum_{i}^{N} \left(P_{Ti} + U_i \cdot P_{Ri}\right)_{\left\{\substack{N=N_T-N_B \\ r=W}\right.}$$
$$P_{NC} = \sum_{i}^{N_Q} \left(P_{Ti} + U_i \cdot P_{Ri}\right)_{\left\{\substack{N_Q=N_T-N_B-N_W \\ r=Q}\right.} + \sum_{i}^{N_W} \left(P_{Ti} + U_i \cdot P_{Ri}\right)_{\left\{\substack{N_W=N_T-N_B-N_Q \\ r=W}\right.} \tag{9}$$

where N_Q is the number of sensors with bitrate *Q*, N_W is the number of sensors with bitrate *W*, N_B is the number of sensors burnt at time *t* and U_i is an on off parameters indicating if the sensor transmits only or if the sensor can receive and transmit data. The algorithm was implemented in 5 different scenarios and the simulation results are shown in Figure 5b). *SC1* represents the scenario where the ignition point was at the center of the terrain without wind. *SC2* and *SC3* represent the scenarios where the ignition point was at a west and east point of the terrain respectively with west and east wind velocities of 3m/s. Finally, *SC4* and *SC5* represent the scenarios where the ignition point was at north or south part of the terrain with winds blowing from north or south at 3m/s respectively. The high sampling rate time zone was assumed, corresponding to *T=2hours* and the fire was monitored for 2 days. It can be observed that P_{NC} is always less than P (by more than a fraction of 2) indicating the achieved energy efficiency of the proposed algorithm. It can also be observed that the power gain reduces with time. This is because the fire burnt area increases with time and so $N_Q \rightarrow N_W$. The power gain depends on the chosen high sampling rate zone (T) and the sampling rate (r).

6 Conclusions

This paper investigated two alternative fire modeling techniques based on CA (Intesys model) and cellDEVS (CD-AUTH model). It was shown that the CA method is characterized by less CPU demands and complexity but does not provide accurate results in windy conditions over sharp terrain. The CD-AUTH model was then used for network topology control of a WSN that target energy efficiency and high time resolution monitoring of forest fire. The effective operational use of the forest fire prediction model resulted to energy efficiency in the WSN of the order of 2.

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