# Sensors–Actuators Cooperation in WSANs for Fire-Fighting Applications

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***Abstract*—Wireless sensor and actuator networks for environmental operations are discussed in this paper. A scenario of a forest being under fire is analyzed. While the forest fire detection is a classical application for sensor networks, here this research area is extended, taking into account actuators and focusing on sensors–actuators cooperation. First, the spreading of the fire is illustrated, adapting a well-known model based on percolation theory and explaining its relations with epidemics propagation models. Then, it is shown how the temperature data gathered by sensors can be used by actuators to automatically perform actions to battle with blaze. Finally, the simulation results are presented, documenting the correctness of the decisions taken by the system and the efficiency of fire-fighting actions related to the sensors density.**

***Keywords-wireless sensor networks; actuators; environmental monitoring; forest fires; epidemics propagation***

## I. INTRODUCTION

Wireless sensor networks (WSNs), being a popular research topic, are considered as a technical solution in large spectrum of applications: from surveillance and tracking of military units at battlefields, to street traffic supervision, controlling goods at storehouses and patients at hospitals. WSNs also fit in a natural way to many environmental operations, where there is a need to gather some data from a vast area. Having in mind recent accidents resulting from environmental disasters, like the death of a group of fire-fighters surrounded by fire in Catalonia, Spain in 2009 or the recent tragedy and the oil leakage in Gulf of Mexico, there is an obvious necessity of developing WSN technology that could help us in remote control and monitoring of areas under a risk of a sudden natural or provoked catastrophe.

However, the focus on gathering environmental data is usually not sufficient. The WSN technology should be supported by an extra capability to react in a case of danger. This stands behind the idea of actuators (sometimes called actors): few but powerful additional nodes having possibilities to take decisions and perform some actions based on data gathered by sensors. Actuators can be also controlled by people, but in the basic concept they are reacting automatically, without unnecessary delays and risking human life in dangerous conditions.

In this paper, a scenario of a fire spreading in a forest is addressed. The forest is monitored by a wireless sensor and actuator network (WSAN) that (a) gathers the temperature data, (b) creates a map of the fire and (c) automatically reacts. The network reaction is realized by fire-fighting groups (actuators) that, in practice, can be humans or machines. In both cases, their actions are supported by the data collected by sensors. Thus, it is a sensor network that delivers the information where and when the fire-fighters should battle blaze.

The main motivation of the presented research is to discuss the interaction and cooperation between the sensors and actuators. Performing computer simulations, we show how the temperature data gathered by sensors can be used to make effective decisions about fighting with fire. The precision of fire predictions made by the sensor network and the correctness of the decisions where to send the fire-fighting units are also analyzed. While adapting well-known models to simulate the spreading of the fire and the temperature in the forest, the models have been merged with the theory of epidemics propagation in order to explain the fire parameters. The proposed system – actuators performing the actions based on a map created with the aid of sensor readings – is tested in forest fires, but it can be also applied in other environmental scenarios, like removing a pollution or performing a rescue action after an earthquake.

The rest of the paper is organized as follows. In Section II, the related work from the area of WSANs is presented, as well as the forest fires modeling and measurements. The models used in this paper are explained in Section III. Simulations results, showing the precision of fire predictions and efficiency of the system when battling the fire are presented in Section IV. Finally, in Section V, we provide conclusions and define further directions of studies.

## II. RELATED WORK

Wireless sensor networks are considered in technical literature from more than 10 years with thousands of papers [1–3] and numerous books [4–6] published. The idea of actuators – more powerful nodes performing some actions on the basis of sensors data – is also common in recent years [7]. Concerning environmental and catastrophe-monitoring applications, recently published works concentrate rather on

communication protocols [8], system modeling [9] or trial experiments [10]. When focusing on cooperation and coordination between network nodes, it is worth to mention papers [11–12], where an interesting, though very general algorithm optimizing actuator operations is presented. First, the integer linear programming technique is used to group the sensors into sets connected with particular actuators. Finally, the actuators are cooperatively taking the decisions allocating the tasks among themselves. It is proposed that the actuators participate in an auction, offering themselves as task executors.

Actuators can be also considered as robots acting with the aid of sensors data, thus, many solutions investigated in the literature concerning robotic systems are very appropriate here. E.g. in [13], a thorough overview on multi-robot coordination can be found. The authors concentrate on methods of intentional cooperation, where the robots work together with a common purpose, which is also the case of WSANs. In [14], a real-time situation with mobile actuators is analyzed. The time delays in communication between actuators are taken into account and the conditions are shown under which the distributed task allocation solution outperforms the centralized one.

When discussing the forest fires, it should be noted a very intensive research in modeling this phenomenon coming from cellular automata theory [15–16]. Two main classes of models were based on (a) self-organized criticality [17–20] and (b) percolation theory [21–22]. The well-known and common model from [21] was also used in the simulations presented in this paper.

Forest fire detection was one of the first environmental applications considered for sensor networks. Due to obvious reasons, there are still not many real measurements in this field. A very valuable data concerning sensors survivability, velocity of the fire edge, temperature gradients, etc. can be found in [23]. By contrast, a report from a fully operational system supporting a group of fire-fighters during a week long campaign is included in [24].

It should be also mentioned that so-called "fire-fighter problem" is an issue known in graph theory: the fire spreading in *n*-dimensional space must be blocked by a minimal number of fire-fighters. However, it is rather weakly related with real forest fires. The interested reader is referred to e.g. [25].

## III. Simulation Model

The main motivation/intention of our research was to analyze the performance of a WSAN network that could measure and gather the temperature in a forest and, in case of detection of a fire, automatically react.

With this purpose, a C++ computer tool was built, intended to simulate the situation in a forest being under fire. Each considered case was simulated at least 10.000 times, in order to obtain statistically reliable results. The simulator had three layers, responsible for modeling: (a) the forest, (b) a network of sensors gathering data and (c) a system of actuators – groups of fire-fighters or machines reacting automatically and extinguishing the fire in specific sectors (sites) of the forest.

The main goal of this work is to analyze the performance of the sensor and actuator network. The models of the fire and fire-fighters actions are simplified and based on numerous assumptions, explained below. However, we believe that the whole model can show the WSAN efficiency, i.e. how the accuracy of the data gathered by sensors influences the reactions of actuators.

The three layers of the simulator are described in the following subsections.

### A. *Forest under fire*

In the considered scenario, a forest ($1260 \times 832$ m$^2$) was divided into $42 \times 32$ hexagonal sites, with a height of a single site equal 30 m (Fig. 1a). In real situations, the rate of spread of the fire depends on many factors, like terrain topography, type of trees, recent rainfall and wind velocity. In this work, we adopted, with slight modifications, a simple fire model presented in [21]. It can be shortly described as follows.

Each forest site can be in one of three states: (a) there can be some trees there, (b) the site can be burning or (c) it can be burnt out to ashes. The evolution of the site states is done in discrete time steps. In each step, a site with trees will start to burn with ignition probability $P_I$, but only if at least one of its six nearest neighbors was burning in the previous time step. Also, in each time step, a site with fire will turn into ashes with burning probability $P_B$. Finally, all sites with ashes remain in this state until the end of the simulation.

This model is very similar to a SIR (Susceptible, Infected, and Removed) model in epidemics [26]. Each of these three modes could be related with the proposed (a), (b) or (c) states, respectively. The probabilities $P_I$ and $P_B$ depict the evolution of the fire (epidemic). The largest is the $P_I$, the faster is the speed of the fire. The smallest is the $P_B$, the more neighbor trees adjacent to a burning tree will be affected.

A threshold of an epidemic is a value, evaluated as a combination of the probabilities $P_I$ and $P_B$, that shows if the epidemic will spread or disappear. This value is evaluated taking into account the topology of the network [26]. In very homogeneous networks, such as the topology described in this paper, the threshold value could be easily approximated as 1 divided by the average node degree $D$ ($D = 6$, in this paper). Taking into account this value, we can select different $P_I$ and $P_B$. In this paper, we have selected $P_I / P_B >> 1 / D$, in order to simulate a fire that spreads quickly across the whole network. Thus, we accepted $P_I = 0.5$ and $P_B = 0.3$.

The simulation of the fire starts from an ignition of a single tree in the middle of the forest. Then, the fire in evolving according to the rules described above. An example of the fire spreading process is shown in Fig. 1b–d.

The states of the sites are observed by sensors deployed in the forest (see Section III.B) and measuring the air temperature. In order to model the temperature $T$ in the forest, we assumed that $T$ depends only on the distance $d$ to the nearest fire. This is based on the well-known fact that the temperature as a function of distance can be modeled as a diffusion process [27]. We assume that in each time step a steady state of temperature

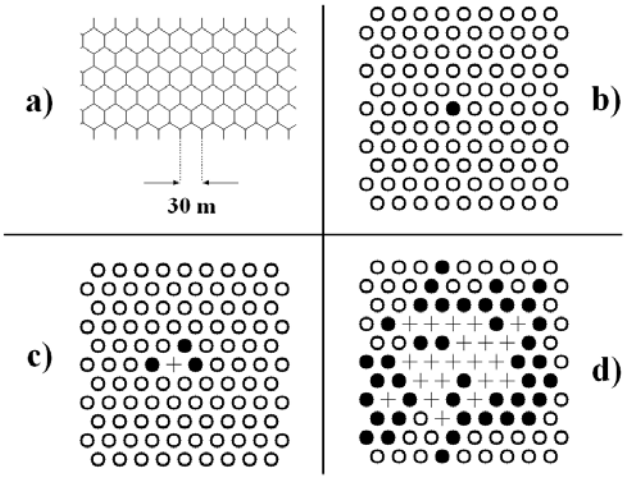


Fig. 1. a) The forest is divided into a grid of hexes: each hex represents a forest site. b–d) The fire is spreading, the steps 1, 2 and 7 are shown. Each forest site can be in one of three states: with trees (o), under fire (•) or covered by ashes (+).

exists and the following relationship holds [28]:

$$T = A / d + B, \qquad (1)$$

where $A$ and $B$ are constants to be determined. Furthermore, we assume that the temperature for two values of $d$ is known, i.e. $T$ (15m) = 90°C and $T$ (150m) = 30°C. Thus, we can calculate the constants $A$ and $B$ and, consequently, the temperature for each distance $d$. Sensors located very close to the fire ($d$ < 15 m) are burning and cannot send any data. On the other hand, sensors being more than 150 m from the fire report the ambient temperature equal 30°C. Thus, each sensor can accurately determine the distance to the closest site with fire, if only it is more than 15 m and less than 150 m away.

While this model is very simple, creating a more realistic one is beyond the scope of this paper. We would like to note, that, if needed, the model can be very easily exchanged by another, more accurate one.

### *B. Sensor network*

In the forest, there is a sensor network deployed, gathering the temperature data. The network consists of a certain number of sensors (from 50 to 500 nodes) located randomly, according to 2-dimensional uniform distribution, and remaining static during the network operation. The sensors are assumed to know their own positions. Also, there are four sinks (control stations) located in the four forest corners. Sinks are supposed to be able to communicate freely with each other. On the other hand, the sensor nodes can send data to other sensors and/or sinks only if they are considered as connected. The sensors transmission parameters are based on typical MICAz sensor motes [29] working in 2.4 GHz frequency band. Their radio power and sensitivity are equal to 0 and –95 dBm, respectively. The path loss for each sensor-sensor or sensor-sink pair is calculated according to the attenuation in vegetation model published by International Telecommunication Union [30]. A medium-dense vegetation, covering 15% of the area, is assumed. Wireless channel fadings are represented by a log-normal random variable with a standard deviation of 3.5 dB, as suggested in [7] on the basis of WSN measurements for outdoor environments. Thus, each pair of nodes is considered as connected if their path loss modified by the channel fading is lower than 95 dB. The sensor nodes that have connection (direct or multi-hop) with one of the sinks can eventually send their data there.

The accepted transmission parameters are chosen to be very representative for wireless sensor technology. MICAz motes are one of the most popular sensors commercially available and commonly used in measurements. Concerning the connectivity model, the parameters that could represent a typical Mediterranean forest are adopted. Though, we would like to mention that in more dense vegetation, the sensors transmission range is expected to be shorter. As a result, many nodes could be not connected, especially if their number would be low, e.g. only 50–150 sensors in the whole forest.

It should be also noted that, as the fire is growing, the network topology is reduced, step by step. Some nodes are burning and some of them are losing the connection with sinks, as their neighbors are destroyed by fire. This effect is taken into account in reported research results.

The temperature readings gathered by four sinks are merged together. On their basis, a map of the fire is created, according to the following rules. For each site in the forest, the data from the sensors located closer than 150 m away is analyzed. A site is regarded as under fire if and only if for each sensor $S_i$ located in the distance $d_i \in$ < 15m, 150m > from the site, the measured temperature $T_i$ suggests the fire is at the distance $d_i$ or closer. Otherwise, the site is considered as covered by trees or ashes. These two states are distinguished from each other using the memory of the previous state, as after the fire there can be only ashes, no trees. Finally, it is possible that the system cannot detect the state of a site, if there are no sensors closer than 150 m from it. The algorithm described above is additionally shown on a flow chart in Fig. 2.

Obviously, the system can make a mistake judging the forest sites. As the rules are defined very conservatively, it is not possible that a burning site is considered as a tree or ashes, although, it can happen that its state cannot be identified. On the other hand, tree sites and, more frequently, ash sites can be incorrectly classified as being under fire.

### *C. Actuators*

A map of the fire is created based on sensor temperature readings and then used by actuators to extinguish the fire in selected sites. The actuators make the decisions where to fight the fire strictly on the basis of this map. The actuators can be the fire-fighters or some mechanical robots able to move through the forest and spread the water onto specific locations.

In this work, we do not aspire to propose optimal strategies for fighting with fire. These strategies are also related to epidemics. A strategy to avoid the spread of an epidemic (or a fire) is called an immunization strategy. In the literature there are many examples of them, such as random strategies, techniques based on the highest node degree, based on graph

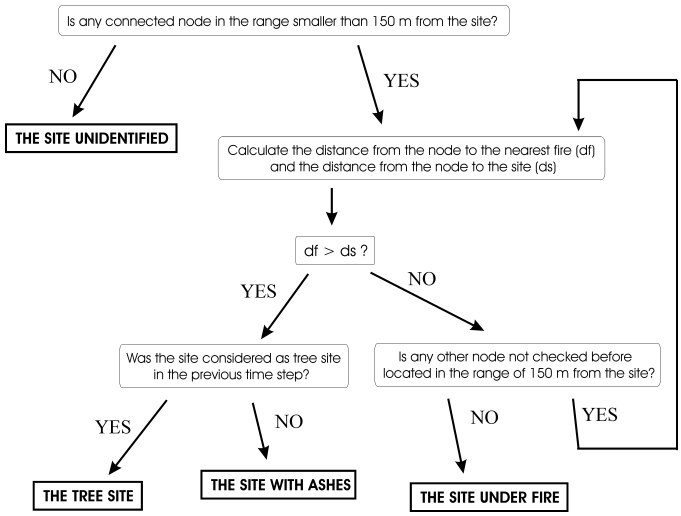


Fig. 2. The rules of creating the fire map.

partitioning techniques, etc. A comparison of them can be found in [31]. As the main goal of this paper is to analyze the performance of sensors and actuators cooperating together, we concentrate on a simple, but well-justified strategy, as described below, and observe the effects of the density of sensor nodes on the actuators efficiency.

Let us accept that we have six fire-fighters (actuators). The number of actuators is chosen on the basis of some initial tests. If the actuators number was much lower, e.g. two or three, their fire-fighting efforts would be not sufficient, even with perfect knowledge about the forest fire. On the other hand, for a significantly larger number of fire-fighters, the whole fire would be very short and the effects of precision of fire predictions would not be clearly visible on simulation results.

All actuators are equipped with powerful radio devices that can easily communicate with control stations (sinks) from each point of the forest. Let us also assume that they cannot act during the first 10 time steps of the fire spreading: the decision about the fire-fighting action must be taken and the actuators must reach the forest. Later, in every time step, each actuator is working in a single forest site, extinguishing the fire there and preventing its spreading to neighbor sites. The time steps are assumed to be very long comparing with the time spent by fire-fighters for moving through the forest. Thus, there are no delays in fire-fighters actions, even if they need to move to a distant forest site in the next time step. Each fire-fighter acts on exactly one site in each time step, extinguishing the fire there and changing the site state to ashes.

The decisions where to send the fire-fighters are taken automatically with the aid of the fire map created with sensors data. The fire-fighters are always sent to the sites that are just burning and are located on the fire edge, i.e. can be easily accessed from the forest border going only through the sites with trees (Fig. 3). Among these sites, six ones are chosen that have a maximum number of neighbor sites with trees, i.e. extinguishing the fire there will stop the fire spread in the most dangerous locations.

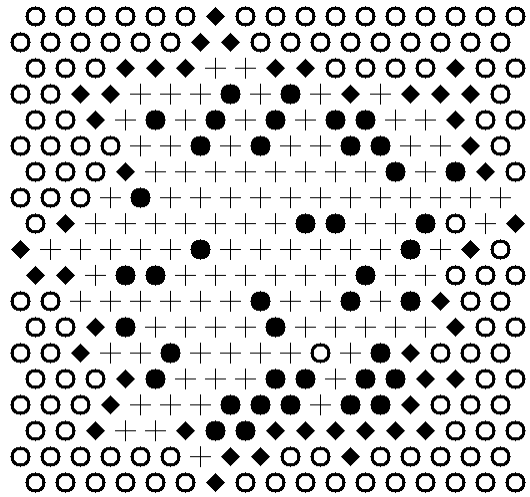

Fig. 3. The fire-fighting actuators can work only on the fire edge, i.e. the burning sites easily accessible from the forest border. These edge sites are marked with black rhombs (♦).

This approach is similar to basic strategies for preventing the viruses or epidemics propagation in communication or social networks [31]. Considering the forest as a network, the sites can be regarded as nodes. In the forest before the fire, the degree of all the nodes (sites) is the same, equal 6, as the forest is modeled as a hexagonal grid. However, in case of fire, a node degree can be reduced. A burning site can spread the fire only to its neighbor sites with trees. Thus, the fire-fighting approach can be seen as an attempt to protect the nodes (sites) with the highest degree (having the large number of neighbor sites with trees).

It can happen that, because of errors on the fire map, the fire-fighters are sent to a site without fire. We assume that such an action is wasted and has no effect.

## IV. Results

In Figs. 4 and 5, two cases of the forests states evolution are compared, the fire-fighter actions are supported by a network of 100 and 500 of sensors, respectively. In both situations, six fire-fighting actuators start to act after first 10 steps when the fire is spreading without control. Comparing the number of sites being under fire in Figs. 3 and 4, we can see that the decisions based on only 100 sensors are not accurate enough to extinguish the fire efficiently. With the data from 500 sensors, the number of sites with fire is decreasing just after the fire-fighters start to work. With only 100 sensors the fire is growing 12 time steps longer. As a result, we are losing about 570 tree sites more (out of 1344 sites in total), frequently sending the fire-fighters to the sites where they are not needed when in the same time the fire is spreading in different places.

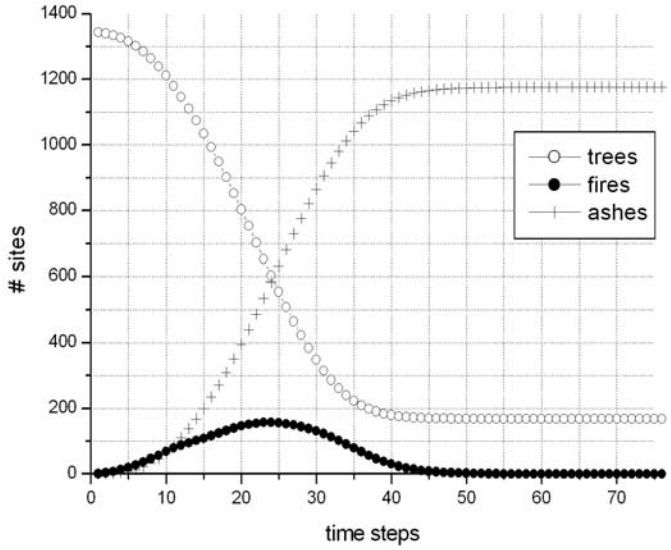


Fig. 4. The forest state evolution. The actions of fire-fighters are based on the data from 100 sensors.

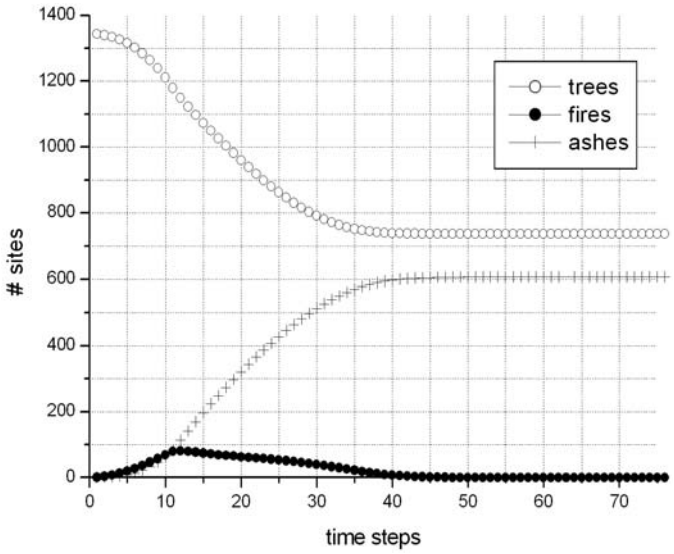


Fig. 5. The forest state evolution when the fire-fighters actions are based on the data from 500 sensors.

The situation can be better understood with the aid of Figs. 6 and 7, where the percentage of sites wrongly identified by the system is shown for the two considered cases. As it was explained in Section III.B, it is not possible that a burning site is identified erroneously. However, it can happen that such a site cannot be identified at all because of lack of sensors in its vicinity. Also, tree or ash sites can be classified as burning ones. It can result in actuators wasting their time after arriving to the locations without the fire. As shown in Fig. 6, with the network of 100 sensors, the total number of wrongly identified or unidentified sites can exceed 75%. For the network of 500 sensors (Fig. 7), it never reaches 12%. While this comparison looks evocatively, the critical difference occurs about 10th time step. Only 5% of errors in the case of 500 sensors does not hamper the efficient actions of fire-fighters and the number of burning sites is gradually reduced. With the network

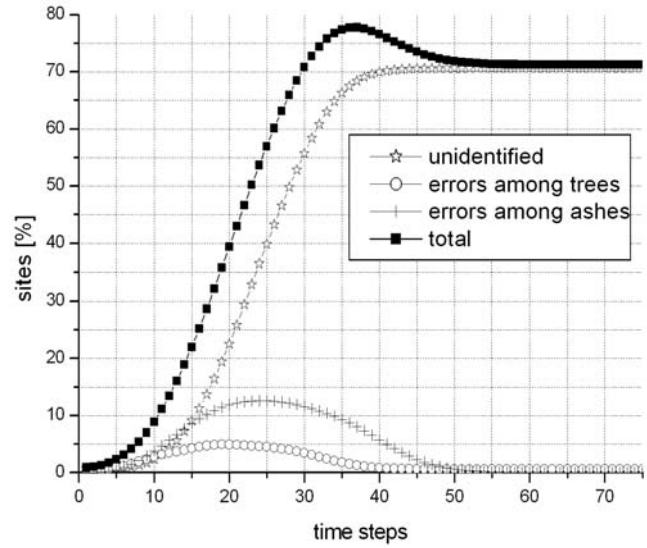


Fig. 6. Wrongly identified and unidentified sites when the network of 100 sensors is used.

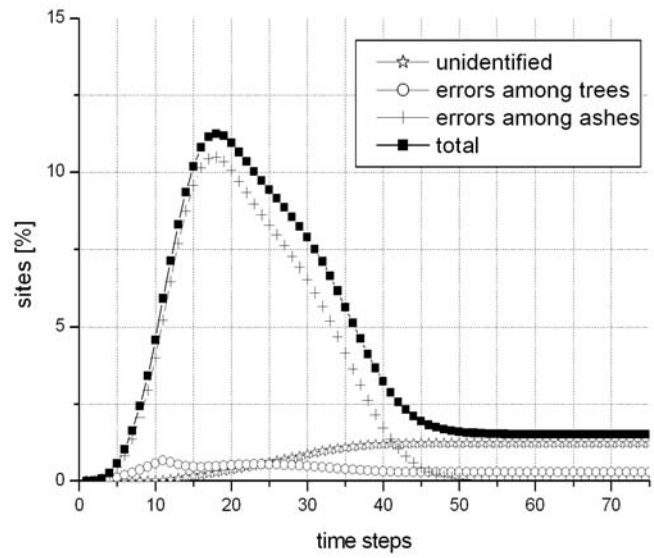


Fig. 7. Wrongly identified and unidentified sites for the network of 500 sensors.

of 100 sensors, there are more than 10% of errors, what results in much more wrong orders where to send the fire-fighters. Usually, most of these errors occurs in the middle of the burnt area (that has no impact on the system performance) and on the fire edge, where they are critical. In consequence, the fire still grows, despite the actions of the fire-fighting actuators.

A more general analysis showing how the system efficiency depends on the number of sensors is presented in Fig. 8. When the number of sensors increases and approaches 500, the ratio of correct system decisions (situation when the fire-fighters are sent to really burning sites) reaches 95%. As a consequence, the number of saved trees also increases up to 55%. However, even 300 sensors (86% of correct decisions) are enough to save nearly 50% of the forest. The next 200 sensors improve the system performance, but the progress is minor.

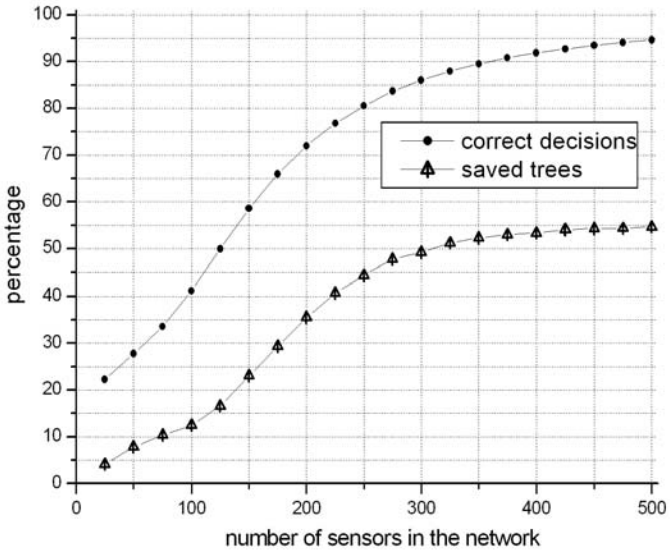


Fig. 8. Percentage of correct decisions (orders for fire-fighters) and saved tree sites.

It should be noted that, concerning the transmission power and propagation model described in Section III.B, the sensors connectivity becomes an issue only if the number of nodes is very low. Even for 100 sensors, 99.6% of them, on average, are connected (directly or in multi-hop way) with one of the sinks.

## V. CONCLUSIONS

As explained in this paper, wireless sensor and actuator networks have capabilities not only to detect a danger in environmental applications, but also to react appropriately. We focused on the example of a forest being under fire. In order to analyze the performance of such a network, we conducted 3-layered computer simulations. First, in order to illustrate spreading of the fire, an appropriate percolation theory based model was adapted. We also discussed the relations between modeling the fire and propagation of epidemics in communication or social networks. Then, a network consisting of sensors gathering the temperature data was considered, delivering it to control stations and, on this basis, creating a map of the fire. Finally, the actions of the actuators were described that used the fire map to choose the best locations in the forest to extinguish the fire. Computer simulations show how the accuracy of the fire map and correctness of the actuators decisions depend on the density of the sensors in the network.

The results presented in this paper were obtained for a set of specific parameters and with some assumptions simplifying the fire spreading and gathering temperature data by sensors. While these results give a solid insight and better understanding of sensors-actuators cooperation, the real efficiency of WSAN-based fire-fighting system strongly depends on environmental parameters (pyrolytic properties of the wood, moisture, wind velocity) and characteristics of the actuators (number of fire-fighters, their efficiency, etc). Further work is still needed in this research area. We plan to continue this topic, investigating more realistic fire spreading models (including the direction of the wind, humidity, terrain diversity), different fire intensities and capabilities of the fire-fighting actuators.

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