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Performance study of wireless sensor and actuator networks in forest fire scenarios

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SUMMARY

Wireless sensor and actuator networks (WSANs) for environmental disaster scenarios are considered in this paper. A fully independent and autonomous WSAN system that is able to detect and extinguish a fire in a burning wildland area is proposed. Although forest fire detection is a classical application for sensor networks, in this paper, this research area is extended, taking into account actuators and their ability to put out fire in the presence of measurement inaccuracy and network degradation. A system architecture is proposed, modelled and discussed. An extensive set of computer simulations analysing the system performance is reported. The presented results show the efficiency of fire-fighting actions depending on the sensors' density and the actuators' mobility. Copyright © 2012 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Wireless sensor networks (WSNs) are a popular research topic, as they are considered a technical solution in a diverse spectrum of applications from surveillance and tracking of military units on battlefields to street traffic supervision or from controlling goods in storehouses to monitoring patients in hospitals. WSNs also fit into 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 deaths of a group of fire-fighters surrounded by a forest blaze in Catalonia, Spain, in 2009 or the oil spill in Gulf of Mexico in 2010, there is an obvious need to develop WSN technology that could help us in the remote control and monitoring of areas under the risk of a sudden natural or provoked catastrophe. According to forecast climate changes, events like forest fires are expected to be even more severe than now [1].

However, merely gathering the environmental data may be insufficient. The WSN technology should be supported by an extra capability that would be able to react in a case of danger. This is the idea behind actuators (also called actors). These few but powerful additional nodes are able to take decisions and perform some actions based on data gathered by sensors. Actuators can be also manually controlled by people, but in their basic concept, they are reacting automatically, without unnecessary delays or risks to human life in dangerous conditions and situations.

In this paper, an architecture of a wireless sensor and actuator network (WSAN) for wildland fire-fighting is proposed and investigated. A forest is monitored by a network that (i) gathers temperature

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data, (ii) creates a map of the fire and (iii) automatically reacts. The network reaction is realised by actuators (fire-fighters) that, in practice, can be humans or machines. In both cases, the data collected by sensors aid and support the course of actions they decide to take. Thus, it is the sensor network that delivers the information about where and when the fire-fighters should act.

Although the general idea of a computer simulation tool [2] and very initial simulation results based on a simplified fire model [3] have been already published, here we present a thorough performance analysis of a WSAN designed for fire-fighting. The main new contribution of this paper can be summarised as a *new architecture of a fully independent and autonomous WSAN based fire-fighting system focused on the sensors' and actuators' operations*. By performing computer simulations, we analyse the precision of fire predictions and the correctness of the decisions about where to send the actuators. We use a detailed fire model taking into account ignition and burning probabilities as well as wind direction and a phenomenon of small branches spreading the fire over long distances. We also address the issue of actuators' mobility, showing how their speed affects the WSAN performance. Finally, we analyse the scenario where some additional sensors are deployed during the fire by operating actuators.

While applying percolation theory models to simulate the spreading of a fire and the temperature in the forest, the models have also been merged with the theory of epidemics propagation in order to explain the parameters of the fire. The proposed system—actuators performing the actions based on a map created with the aid of sensor readings—is considered for fire-fighting purposes, but it can be also applied to other environmental scenarios, such as flooding, removing hazardous waste or carrying out a rescue operation after an earthquake.

The remainder of the paper is organised into six sections. Because of the interdisciplinary character of our study, the related work analysis is divided into two sections. In Section 2, the topic of sensor and actuator networks for environmental applications is discussed. Then, in Section 3, the existing forest fire models are considered, and the one selected for the investigations is defined. The entire proposed architecture of the fire-fighting system, that is, sensors, base stations and actuators and their operations, is presented in Section 4. The computer model used in order to carry out the performance analysis is depicted in Section 5. Section 6 contains the simulation results, and Section 7 concludes the paper.

2. SENSORS AND ACTUATORS

Wireless sensor networks have been considered in technical literature for more than 10 years now, with thousands of papers and numerous books having been published. Starting from well-known survey papers [4, 5], the topic evolved and was then split into many sub-disciplines according to numerous WSN applications. On the subject of environmental WSNs, although many successive deployments were reported [6–10], there are still ongoing challenges to face before large-scale WSNs are widespread and expansively used in practical applications [11].

Wireless sensor networks are also commonly considered as a means that is able to monitor an endangered forest area and detect fire [12]. The basic data gathered by simple wireless sensors, that is, temperature, humidity and air pressure readings, can be used to determine the presence of fire [13]. Some researchers also explored the idea of sensors equipped with digital cameras, as an option for collecting more accurate information [14, 15]. However, video sensors are characterised by a higher cost as well as larger processing and energy supply requirements, which in turn make vast WSN deployments very difficult. In this paper, we assume that sensors have basic capabilities and can deliver the temperature data.

The idea of actuators arose a few years ago as a WSN complement, resulting from a large number of research studies [16–19]. Actuators refer to a group of resource rich machines that are usually mobile, are able to perform some actions (typical for an application), have strong communication and processing capabilities and have large energy supply [20]. Actuators can and should cooperate between each other in order to enhance their performance [21, 22].

Actuators can also be considered as robots acting with the aid of sensor data; thus, many issues investigated in the literature concerning robotic systems, such as intentional cooperation [23] or

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communication with real-time delays [24], are very appropriate here. As to actuators in environmental and catastrophe-monitoring applications, recently published papers concentrate rather on communication protocols [25], system modelling [26] or trial experiments [18].

Although there are many research studies on the WSAN topic already presented in open literature, only a few of them consider that actuators' actions are closely dependent on sensor data. Here, we assume that actuators act on the basis of sensor readings only; thus, the whole WSAN is fully autonomous and is able to work without human control. To the best of the authors' knowledge, a complete analysis of such an autonomous WSAN system oriented on an environmental or disaster application is still missing. Some similar issues can be found in [21, 22], where actuators negotiate between themselves how the actions should be distributed. However, it is not explained how the sensor data influences the actuators' decisions.

In recent years, the WSN concept was also added to some ideas from the field of unmanned aerial vehicles (UAVs). Surprisingly, UAVs are considered as sensor nodes with enhanced capabilities rather than as actuators. UAVs with specialised on-board sensor platforms can easily perform sensing and monitoring functions [27, 28]. They can be also applied to target tracking and localisation [29, 30]. As to their mobility, dedicated schemes for vehicle control and coordination were proposed [29, 31]. UAVs were also considered for wildfire detection, which can be treated as a special case of monitoring and target tracking applications. A real-time algorithm for tracking the perimeter of fire was proposed, however without testing it in practice [32]. Machines able to perform unmanned firefighting actions do not yet exist, but with current aerial vehicle technology, they could be developed. There are also numerous types of specialised ground units, and new ones are being designed [33].

For the purpose of this paper, it is assumed that a few such units exist in the considered network. They can be pilot-driven or unpiloted units, aerial or ground ones or they can even be groups of firefighters. Different mobility limitations are analysed in a later part of this paper taking into account all of these cases.

3. FOREST FIRES

In order to properly analyse the application case considered in this paper, a suitable model of the environment, that is, a forest under fire, is required. Very intensive research in modelling this phenomenon comes from the cellular automata theory [34, 35]. Two main classes of models are based on (i) self-organised criticality [36–38] and (ii) percolation theory [39–41]. A well-known and common model from [41] is also a basis for the simulations presented in this paper.

According to this model, it is assumed that a forest can be divided into a large number of equal hexagonal cells called forest sites. Each forest site can be in one of three states: (i) there can be some trees there; (ii) the site can be burning or (iii) it can be burnt out and reduced to ashes. The fire spread is analysed in discrete time steps. At each step, a site with trees will start to burn with an ignition probability P_{I} for each of its burning neighbour sites, that is, $1-(1-P_{\mathrm{I}})^b$, where b is the number of burning neighbour sites. Also, at each time step, a site with fire will be reduced to ashes with a burning probability P_{B}. Finally, all sites with ashes remain in this state until the end of the simulation (Figure 1). Unlike in [41], we do not consider new trees appearing on ash sites, as the time scale of our model is much shorter (hours or days instead of decades of years).

This model is very similar to the susceptible, infected and removed model in the epidemics propagation theory [42, 43]. Epidemic models are used in several research areas, such as social networks, virus spreading and so on. In telecommunication networks, there are a few such proposals and a previous publication by the authors where more details about the application of epidemic networks to model a failure propagation can be found in [44]. The probabilities P_{I} and P_{B} depict the evolution of the fire (epidemic). The larger the P_{I}, the faster the speed of the fire. The smaller the P_{B}, the more the neighbouring trees adjacent to a burning tree will be affected.

A threshold of an epidemic is a value, evaluated as a ratio of the probabilities P_{I} and P_{B}, which shows if the epidemic will spread or disappear. This value is evaluated by taking into account the topology of the network [42]. In homogeneous topologies, the degree distribution peaks at an average degree (D') and decays exponentially for $D \gg D'$ and $D \ll D'$. In homogeneous networks, such as the topology described in this paper, the threshold value could be easily approximated as 1

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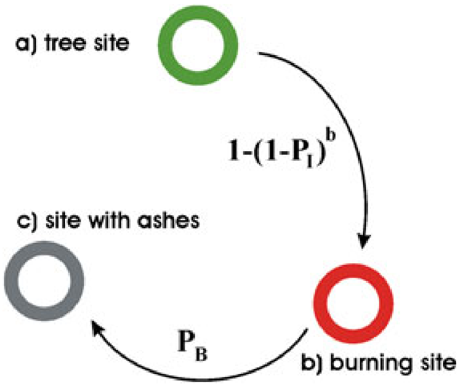

Figure 1. Possible transitions between the states of a forest site.

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 values. In this paper, we have selected $P_\mathrm{I}/P_\mathrm{B} \gg 1/D$, in order to simulate a fire that spreads quickly across the whole network.

In reality, fire propagation is not so homogenous. The shape and velocity of a fire front, called the rate of spread [45], depends on a large number of factors, such as wind, terrain slope, topographic conditions, fuel (tree) type and moisture content, humidity and weather conditions [46]. Apart from the simulation analysis reported in [47], some measurement campaigns were performed [48, 49], resulting in a bulk set of data describing the shape and rate of spread of fire in different scenarios. Assuming spatially invariant conditions, it was shown that the fire perimeter expanded as an ellipse with the fire ignition point being in one of the ellipse foci. On this basis, an empirical formula was proposed that gave the relation between the wind speed and the shape of the ellipse. The ratio L between the lengths of major and minor ellipse axes is shown as follows [45]:

$$L = 1 + 0.0012 \cdot v^{2.154}, \tag{1}$$

for v (the wind speed) not higher than 50 km/h.

We applied the above formula to the forest fire model. Instead of keeping the ignition probability P_I equal in the whole forest, we made it dependent on the wind direction and speed. As P_I describes the probability of the fire spreading from one site to its neighbour, it now also depends on the neighbouring site being location: windward, leeward or perpendicularly when being compared with the wind direction. Each site has six neighbours; as a result, we have six different ignition probabilities (see Figure 2). In each case, the initial probability P_I is multiplied by the length of the ellipse radii and then normalised in order to have the average ignition probability equal to P_I:

$$P_\mathrm{I}^j = P_\mathrm{I} \cdot l_j \cdot \frac{6}{\sum_{k=1}^{6} l_k}, \tag{2}$$

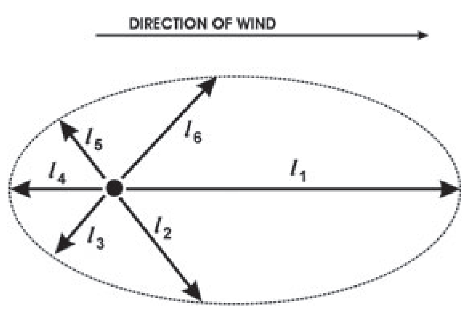

Figure 2. The influence of the wind speed on the ignition probabilities.

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where P_{I}^{j} is the ignition probability in the jth direction and l_j is the jth length of ellipse radii from its focus, as shown in Figure 2. The radii l_j are calculated for a unitary ellipse with minor axis equal to 1 and major axis equal to L. Note that in a general case, the forest, terrain and weather conditions can also be taken into account in the model described in (2) when they are not homogenous. If only suitable data are available, P_{I} should be accordingly modified as a function of geographical coordinates (x, y). On the other hand, in a special case of homogenous conditions and no wind, we obtain $L = 1$ and $P_{\mathrm{I}}^{j} = P_{\mathrm{I}}$.

The forest fire model was extended with a phenomena of small branches spreading fire over long distances when travelling with the wind [50]. Each tree site located at a distance d from a burning site will start to burn with the following probability:

$$P_{\mathrm{B}} = K \cdot \mathrm{e}^{d}, \tag{3}$$

where K is a constant dependent on the weather conditions, humidity and fuel (tree) type. With the lack of data regarding the frequency of burning branches spreading during forest fires, we chose such value of K so that the average number of effective burning branches was between 4 and 5 in each simulated scenario. This value of K gives a significant number of effective burning branches in each scenario, but at the same time, it does not dominate the phenomena of fire spread.

4. PROPOSED SYSTEM ARCHITECTURE

In this paper, we propose an architecture of an entire system designed for wildland fire-fighting. The system gathers the air temperature data delivered by tiny sensors and, on its basis, makes decisions where to send actuators (fire-fighters) in order to extinguish the fire. Its main goal is to save as large a part of the forest as possible, that is, maximise the area not affected by the fire.

For the purpose of the system, the controlled forest is divided into a number of homogeneous sites. In this paper, we assume the hexagonal sites with a height of a single site equal to 30 m; however, the shape and size of the sites can be adjusted depending on how detailed the required data are.

As for the presented model, each forest site can be in one of three states: (i) there can be some trees there; (ii) the site can be burning or (iii) it can be burnt down to ashes. The system decisions are taken repeatedly, one per a certain time step. This time step is assumed to be enough for a single actuator to extinguish the fire in one site (i.e. to change its state to ashes) and move on to another site. It can take a few minutes or even half an hour. This time is equal to the time step of the analysis of forest fires, as described in Section 3. Note that the issue of recovery from topology changes is not crucial here, as the time period of a few minutes is enough for a routing protocol to adjust the table entries [51].

In order to work properly, the system consists of three layers: sensors, base stations and actuators (see Figure 3). They are briefly described in the following three sections.

4.1. Wireless sensors

Sensors are deployed in a forest before the fire may occur. Due to the non-homogeneity of the forest vegetation, it is almost impossible to deploy the sensors in any regular grid. The system should be able to perform well even in a random distribution of sensors.

The main sensor's function is to locate the fire. This can be achieved with many sensor types, such as light or temperature sensors, or even cameras. In this paper, we analyse the system with sensors measuring the ambient air temperature T. We assume that T depends only on the distance d to the nearest fire. This is based on the well-known fact that temperature as a function of distance can be modelled as a diffusion process [52]. We also assume that in each moment of time, a steady state of temperature exists, and the following relationship holds [53]:

$$T = A/d + B, \tag{4}$$

where A and B are constants to be determined with some initial measurements. If A and B are known, the temperature for each distance d can be calculated. As the equation (1) can be reverted,

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Figure 3. The network architecture: base stations, actuators (these can be UAVs or helicopters) and sensors deployed in a monitored area. Sensors are communicating with base stations by multiple hops. Actuators are assumed to have stronger radio transceivers and can communicate directly.

for each temperature reading, the corresponding distance d can be estimated. Of course, sensors located very close to the fire (below the *burning range*) are burning and cannot send any data, just as sensors that are further than the *sensitivity range* from the fire report ambient temperature, but their data are useless. Thus, each sensor can only accurately determine the distance to the closest fire, if it is further away than the burning range and closer than the sensitivity range.

Although 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 for a more accurate one.

The temperature readings together with sensor geographical coordinates are sent hop by hop through other sensors to one of the base stations. Sensors should know their own positions—they can be programmed during the deployment process, or a localisation protocol may exist [54–56]. Sensors can send data to other sensors and/or base stations only if they are connected with a base station either directly or by multiple hops (see Section 5.2 for the accepted connectivity model). During a forest fire, the network topology is reduced, step by step. Some nodes are burning, and some of them lose their connection with the base stations when their neighbours are destroyed by fire. As the sensors should know their positions, geographical routing and MAC protocols are suitable in order to deliver the data to the base stations. Although their details are beyond the scope of this paper, there are numerous algorithms already proposed that can be found in the open literature [57, 58].

4.2. Base stations

In the forest, there is also a certain number of base stations. These are able to communicate freely with each other. Their processing abilities are also much higher than in the case of the sensors. Base stations gather the temperature readings delivered by the sensors. One of the base stations acts as a network centre and merges all the data together. On this basis, a map of the fire is created, according to the following rules:

At each time step, the data from the sensors located closer than the sensitivity range is analysed; this is carried out for each site in the forest. A site is regarded as under fire if and only if for each connected sensor S_i located in the distance $d_i \in <$ burning range, sensitivity range $>$ from the site, the measured temperature T_i suggests the fire is at the distance d_i or closer. Otherwise, the site is

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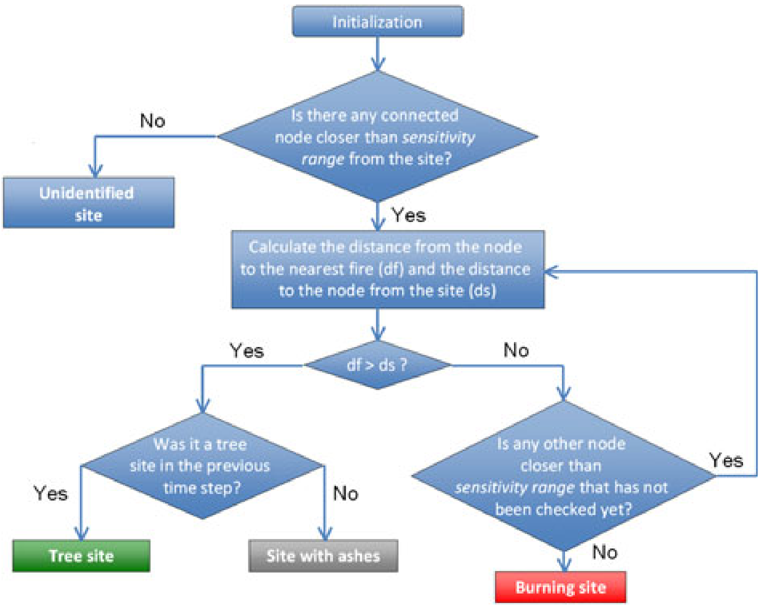

Figure 4. The algorithm of creating the fire map. This is performed for each forest site.

considered as covered by trees or ashes. These two states are distinguished from each other by using the memory of the previous time step, as after the fire there can only be ashes and no trees. Finally, it is possible that the system cannot detect the state of a site, if there are no sensors closer than the sensitivity range. The algorithm described above is additionally shown on a flow chart in Figure 4.

Due to lack of accuracy, the system can make a mistake when judging the states of forest sites. As the rules are defined very conservatively, it is not possible (assuming correct temperature measurements and reporting) that a burning site is considered as a tree or ashes, although it is possible that its state cannot be identified. On the other hand, tree sites and, more frequently, ash sites can be incorrectly classified as being on fire. In general, this pessimistic behaviour is convenient in these sorts of scenarios.

4.3. Actuators

The third network layer consists of actuators. All actuators are equipped with GPS receivers and powerful radio devices that can easily communicate with a base station from each point of the forest. They are machines (UAVs and ground vehicles) able to move quickly through the forest and spread water onto specific locations. They can also be people, but here, it is assumed that the decisions as to where to send them are taken automatically by the system.

In each time step, the system creates the fire map based on sensor readings. Then, each actuator is sent to a different burning site in order to extinguish the fire there and prevent it from spreading to neighbour sites. The decisions as to where to send the actuators are crucial for the system performance.

First, the set of the burning sites located on the fire edge is distinguished. These sites can be accessed by fire-fighting machines (actuators) from the border of the forest and going only through the sites with trees. Moreover, the fire in the edge sites is the most dangerous, as it can easily spread to the neighbouring sites that have trees.

For the ith burning site located on the fire edge, the so called fire danger index (FDI) is calculated, according to the formula below:

$$\mathrm{FDI}_i = \sum_{j=1}^{6} P_1^j \cdot F_i^j, \tag{5}$$

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where $F_i^j = 1$ if the jth neighbouring site is still covered by trees and $F_i^j = 0$ if it is on fire or contains ashes. Thus, FDI shows how dangerous the fire in a site is, that is, the expected number of neighbouring sites to be ignited in the next time step.

Next, for the system with N actuators, N sites with the highest FDI are chosen. These are the most dangerous fire spots, and the actuators should be sent there. However, as the actuators have limited speed, some of the selected sites could be out of their range. Thus, if the system cannot match the chosen sites with actuators in such a way as to have the sites in the actuators' range, one or more of the chosen sites must be rejected. Then, another site with a smaller FDI but being within the range of an actuator is selected. In the worst case scenario, when the system cannot select N burning sites located within the actuators' range, some of the actuators will only be heading towards their nearest burning sites but not actually extinguishing the fire.

The presented approach is similar to basic strategies for preventing viruses (immunisation techniques) or epidemics propagation in communication or social networks [59]. 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 to 6, as the forest is modelled 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 neighbouring sites with trees. Thus, the fire-fighting approach can be seen as an attempt to protect the nodes with the highest degree (having the largest number of neighbouring sites with trees). In the literature, there are many examples of random strategies, techniques based on the highest node degree, based on graph partitioning, and others. A comparison of them can be found in [59]. These strategies could be included in our model without major changes.

It is also possible 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. Statistics of such events are reported in Section 6.

To summarise, we can describe all the activities of the fire-fighting system as four operations:

(1) The sensors gather temperature data and send them to the base stations.
(2) The fire map is created.
(3) The decisions where the actuators should act are made and sent to them.
(4) The actuators move to the selected sites and extinguish the fire there.

These four operations make up a single time step of the working system and are performed cyclically. The length of the whole time step is determined by the length of the fourth operation and can be easily adjusted to the speed and efficiency of real fire-fighting machines.

5. COMPUTER SIMULATION MODEL

With the aim of analysing the proposed system, a computer simulation tool was prepared. Because the tool had to simulate not only the behaviour of a sensor network, actuators' mobility and actions and radio connectivity but also the forest and the fire spreading through its sites, we decided to build a completely new simulator using C++ language. Despite some simplification and assumptions needed in order to have the simulations feasible, we believe that the simulator can clearly demonstrate the fire-fighting system efficiency in two crucial aspects: the influence of the accuracy of sensor readings and the impact of actuator mobility. In this section, the simulator and the selected parameters will be briefly described.

5.1. The forest on fire

A forest (2494×1375 m^2) was divided into 80×50 hexagonal sites, with a height of a single site equal to 30 m (Figure 5(a). Each simulated case started from the ignition of a single tree in the middle of the forest. Then, the fire evolved according to the model described in Section 3. We accepted $P_B = 0.2$ and $P_I = 0.25$, fulfilling the condition for quickly spreading fires ($P_I/P_B \gg 1/D$), and considered two values of wind speed: 5 and 20 km/h. An example of the fire spreading process is shown in Figure 5(b)–(d). The burning and sensitivity range values were assumed to be 15 and 150 m, respectively. Note that, as a homogenous forest is assumed (regarding the terrain slope and

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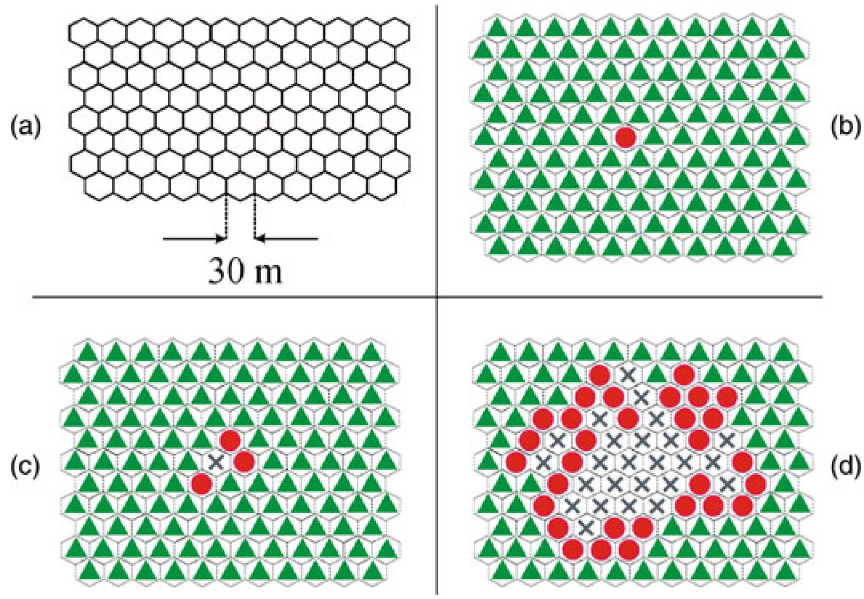

Figure 5. (a) The forest is divided into a grid of hexes: each hex represents a forest site. (b)–(d) The fire is spreading, and steps 1, 2 and 6 are shown. Each forest site can be in one of three states: with trees (green triangles), on fire (red circles) or covered by ashes (grey crosses).

vegetation conditions), the direction of the wind is not relevant. Thus, the wind blows from the west to east (from left to right), as indicated in Figure 2. The fire always ignites in the centre of the forest.

5.2. *Sensors and connectivity issues*

The sensor network deployed in the forest consisted of a certain number of sensors (from 100 to 1000 nodes, i.e. their density was from 30 to 300 per km^2), located randomly according to two-dimensional uniform distribution, and remaining static during the network operation. There were four base stations located in the four corners of the forest. The sensors' transmission parameters were based on typical MICAz sensor motes [60] working in a 2.4-GHz frequency band. Their radio power and sensitivity were equal to 0 and −95 dB m, respectively. The path loss for each sensor–sensor or sensor–base station pair was calculated according to the model of the attenuation in vegetation published by the International Telecommunication Union [61]. A medium-dense vegetation, covering 15% of the area, was assumed. Wireless channel fadings were represented by a log-normal random variable with a standard deviation of 3.5 dB, as suggested in [19] on the basis of WSN measurements for outdoor environments. Thus, each pair of nodes was considered as connected if their path loss modified by a channel fading was lower than 95 dB. The sensor nodes that had connection (direct or multi-hop) with one of the base stations were eventually able to send their data there.

The accepted transmission parameters were chosen to be very representative for wireless sensor technology. MICAz motes are one of the most popular commercially available sensors and commonly used in measurements. As for the connectivity model, the adopted parameters can represent a typical Mediterranean forest. We would like to note, however, that in more dense vegetation, the sensors' transmission range is expected to be shorter. In such a case, many nodes might be not connected, especially if their density were to be low, for example, below 70 per km^2.

5.3. *The fire-fighting system*

For the purpose of the simulations, we set up five actuators in the network. The number of actuators was chosen on the basis of some initial tests. If the actuators' number was much lower, for example, two or three, their fire-fighting efforts would not be sufficient, even with perfect knowledge

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of the forest fire. On the other hand, for a significantly larger number of actuators, the whole fire would be very short, and the effects of fire prediction precision would not be clearly visible on simulation results.

The actuators could not move through the forest sites that were burning. With UAVs, it would be possible, but we analysed a scenario where ground vehicles (or even groups of fire-fighters) could also be used.

Finally, we assumed that the actuators could not act during the first 10 time steps of the fire spreading. It was motivated by the fact that the system required some time for it to take the decision of starting the fire-fighting operation and for the actuators to reach the border of the forest.

6. SYSTEM PERFORMANCE RESULTS

An initial analysis showing how the system efficiency depends on the number of sensors is presented in Figure 6. In this case, it is assumed that the actuators can move freely between sites having unlimited speed, and the considered wind speed is $v = 0$. Results show that having less than 300 sensors gives a very poor performance, saving only less than 20% of the forest. From 300 to 600 sensors, there is a reasonable cost–improvement ratio. More sensors (reaching 1000 in the figures) do not significantly improve the performance.

It should be noted that, pertaining to the transmission power and propagation model described in Section 5.2, the sensors' connectivity becomes an issue only if the number of nodes is very low. Even for 300 sensors, 99.7% of them are connected (directly or in multi-hop way) with one of the sinks.

The results, taking into account different wind velocities and limited mobility of the actuators, are depicted in Figures 7 and 8. The percentage of saved forest sites as a function of the number of sensors is shown for four cases. In each time step, the actuators can move to 3, 5, 10 and 20 sites, respectively. Thus, when making the decisions as to where to send the actuators, the WSAN system may consider only a subgroup of burning sites: namely those located in the vicinity of actuators. Moreover, when their speed is limited, the actuators cannot move quickly between different burning sectors. These factors seriously degrade the system's efficiency. On the other hand, the actuators' mobility limited to 10 sites per time step is clearly enough to obtain good results. Higher mobility values give no significant performance improvement.

With reference to the wind effect, the shape of the fire perimeter becomes more elliptical when the wind velocity increases; however, there is no meaningful influence on the actuators' performance. Paradoxically, comparing the scenarios with wind velocities 5 and 20 km/h, a slightly larger number of trees saved can be observed despite the stronger wind. This can be explained by the fact that with

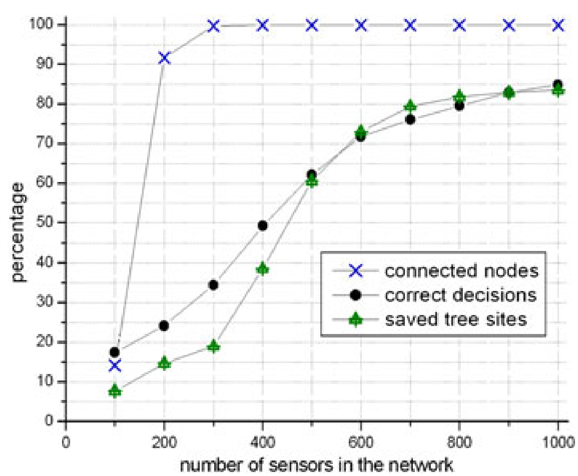

Figure 6. Percentage of connected nodes, correct system decisions and saved tree sites in the scenario with no wind and unlimited mobility of the actuators.

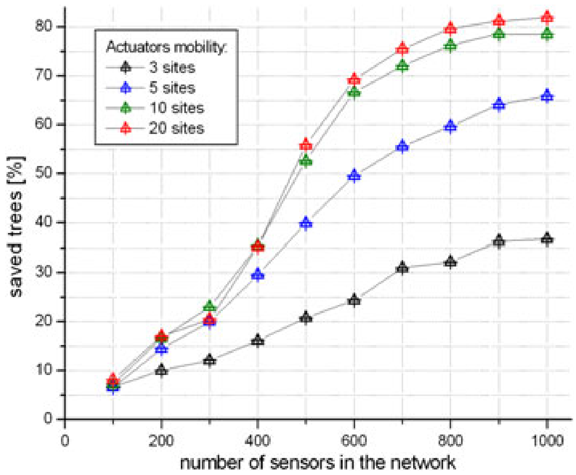

Figure 7. Percentage of saved tree sites in the cases of limited actuators' mobility. Wind speed is 5 km/h.

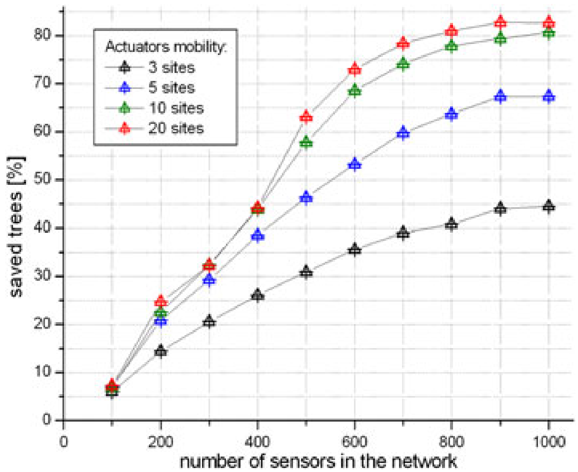

Figure 8. Percentage of saved tree sites in the cases of limited actuators' mobility. Wind speed is 20 km/h.

the stronger wind, the most dangerous fire spots can be easily located (as the fire propagates with the wind), and the actuators can focus their efforts on a single forest sector without moving over large distances. Nonetheless, it should be noted that we assumed the same P_I in both scenarios (having no reliable data on it), modifying the fire perimeter shape only (equations 1 and 2).

Finally, we consider a scenario where the actuators may deploy additional sensors during their fire-fighting actions, that is, after the fire has started. The actuators, during their movement through the forest, deploy some extra nodes. In order to do that, they are continuously calculating their distances to their closest sensor shown on the fire map. If the distance is larger than 50 m, a new sensor is dropped. Thus, the additional sensors are filling the gaps in the sensor network coverage. The new sensors are usually deployed very close to the fire, as they are put on the actuators' paths.

The scenario with sensors deployed by actuators is compared with the other one where the deployment takes place only prior to the fire (see Figure 9). The additional sensors clearly give a certain improvement, but the final number of sensors used in the network also increases. However, if the WSAN network is planned for the larger forest area, for example, hundreds of square kilometres, it is really advantageous to decrease the initial sensor density. The extra sensors will be deployed only in a region affected by fire, which is hopefully significantly smaller than the whole forest area.

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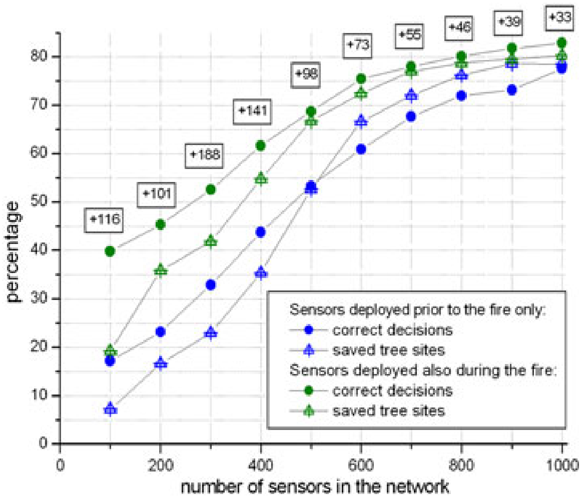

Figure 9. Two scenarios compared: the sensors are deployed only prior to the fire or also during the fire. The values in squares indicate the average number of additionally deployed sensors. The wind speed is 5 km/h, and the actuators' mobility is limited to 10 sites.

7. CONCLUSIONS

Wireless sensor and actuator networks have capabilities not only to detect a danger in environmental applications but also to react appropriately. In this paper, we proposed an architecture of a WSAN system designed to cope with wildland fires. The system monitors a forest by gathering the temperature data, creates the fire map and automatically reacts sending the actuators to extinguish the fire at the crucial burning sites. We modelled the whole system consisting of sensors, actuators and base stations and explained the cooperation between the system elements. The fire spreading in the forest has also been modelled. On this basis, we analysed the system performance using computer simulations. This demonstrated how the system efficiency was dependent on the sensors' density and the actuators' mobility. Moreover, we indicated the optimal values of these parameters.

The presented results have shown, under different fire spreading scenarios, the upper bounds in sensor density required to achieve a suitable level of accuracy. The actuators' mobility has also been analysed, showing that higher mobility values do not give significantly increased performance. Similar result occurs when the wind effect is introduced; in fact, there is no meaningful influence on the actuators' performance if the wind velocity increases. Finally, an increase in sensor density related to the actuators' mobility area has been analysed. As expected, only if the initial density values are very small, these actions are useful.

To conclude, the presented results in the network scenario show the efficiency, in terms of accuracy, depending on sensor density and actuator behaviour. This model could be easily extended and applied to other similar network disaster scenarios, such as flooding, earthquakes or contamination leakages.

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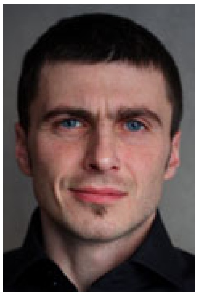

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