Wildfire impact on deterministic deployment of a Wireless Sensor Network by a discrete event simulation.

T. Antoine-Santoni, J.F. Santucci, E. De Gentili, *Member*, *IEEE*, and B. Costa.

***Abstract*—Detecting and providing evolution informations of the wildfire can be a challenge for Wireless Sensor Networks. The network performance is directly related to the placement of the sensors within the field of interest. In this paper, we address the problem of wireless sensor deployment, for the purpose of following wildfire phenomenom. Based on a discrete event simulation using DEVS formalism, we show that the complexity of the fire position estimation is dependant of network deployement. We test four strategies of deployement and we show the limit of deterministic deployment in simple wildfire scenario.**

***Index Terms*—Deployment, DEVS, Fire, Simulation, WSN Simulation, WSN.**

I. Introduction

DEVASTING forest fire regularly damage all continents over the worlds. In common with numerous other countries over the past decade, vast forested regions were destroyed by fire in Corsica. Firemen try to find different solutions to detect blossoming of wildfire. It would be very useful to have a predictive tool that can be used for detection of forest fire. Nowadays Wireless Sensors Network (WSN) appear like an open issue for environmental monitoring. Networks of wireless sensors are the result of rapid convergence of three key technologies:

- Computing/Internet : computing power is becoming small and inexpensive enough to add to almost any object. networks of computers facilate collaboration trough information and resoure sharing
- Sensor : miniaturization, micromachining and low cost leads to smaller sizes, low power, lower costs. Alows to monitor with higher granularity. many types of sensors and more on the way
- Wireless/ Antennas : Spans a host of technologies including Bluetooth and Wifi networks, cellular and satellite communications.

A sensor node combines the abilities to compute, to communicate and to sense [12]. The sensor sends such collected data, usually via radio transmitter, to a command center (sink or Base Station) either directly or through a data concentration center (a gateway). In a sensor network, different functionalities can be associated with the sensor nodes. A wildfire application and a development of detection tool appear essential for many reasons [3]:

- Prevention: a technology to collect environmental data.
- Detection (fight): mesh network architecture to square a zone and inform firemen of fire evolution.
- Monitoring: detecting critical areas with birth conditions of forest fire.

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T. Antoine-Santoni , J.F. Santucci, E. De Gentili, B. Costa are with the SPE UMR CNRS 6134 laboratory, University of Corsica, Quartier Grossetti, 20250 Corte, France, (e-mail: antoine-santoni, santucci, gentili, bcosta@univ-corse.fr).

Environmental monitoring must be environmentally appropriate, which requires easy to install, low maintenance, non-toxic and inexpensive instrumentation. In order to monitor wildfires and impending wildfire conditions, the Firebug project [11] decided to use wireless, low-power sensor technology to collect environmental data (temperature, humidity, barometric pressure). In [11] it described the design of a system for wildfire monitorig incorparating Wireless Sensor Network with a external communication system. The Firebug project is ccomposed of a network of GPS-enabled, wireless thermal sensors, a control layer for processing sensor data, and a command center for interactively communicationg with the sensor network. The main results of this study the passage of the flame front before being scorched, with temperature increasing and barometric pressure and humidity decreasing as the flame front advanced. In [9] the authors show a system design approach for a WSN based application that is used to measure temperature and humidity as well as being fitted with a smoke detector. In [10], the main objective is to study and test a WSN system for wildfire monitoring and alarm signalling. The system detect a small fire with a focus on reactivity, and robustness reliability.

These diferents results show the capacity to detect a wildfire however the evolution of fire in a great area and the impact of wildfire on network architecture are not considered. That is justified by the cost on the deployment of such system. The simulation plays a important role in this case to understand the behavior of WSN with several nodes in wildfire under differents conditions or different deployments. To understand the behavior of Wireless Sensor Network under different conditions, we need to describe reactions of this complex system. Modeling and simulation appear like an essential aspect to understand the specific behavior of Wireless Sensor Network under specific conditions. The network simulation for sensors is a challenging problem as it has faithfully to model the constraints hardware and environment cases.

The paper is organized as follows : Section 2 introduces brievely tthe state-of-art of the modeling with DEVS in Wireless Network and the DEVS formalism. Section 3 we present our approach based on DEVS description of Wireless Sensor node. The results of simulation are presented in Section 4 with an analysis of collaboration of wireless sensor nodes under different deployments. Finally, in Section 5 we give some conclusions and directions of our future research works.

II. Wireless Sensor Network Modeling

A. Survey of existing works

It seems important to us to represent the different basics hardware components of the node. Our generic approach leads us to define behaviour of different components. We try to delimit the different reactions of the node units to move towards the description of a general behaviour of a sensor using a discrete event formalism DEVS. A discrete event approach like DEVS formalism allows to model the dynamics of the system based on the state, space, measured in a qualitative and quantitative manner, and a continuous time scale. The advantages of this formalism for description of complex system in discrete-event scale appear clearly in number field of research. However definition of sensor network and in particular sensor node don't exist. As sensor networks gaim more importance in the research communities, it's very crucial to show the advantages of DEVS formalism and to have a simulator with a modular structure. The use of this formalism in accordance with its definition implies for this research area two essential points: a modeling specification step and consequently a clear interpretation of simulations results in the real world and a non ambiguous operational semantic step allowing the introduction of a formal specification of mechanics of simulation using an abstract simulator. Some works exist for the modeling of wireless sensor networks using DEVS. In [14] , we can see the using of Cell-DEVS to model routing protocol AODV. In this paper, DEVS is used to formally specify discrete events systems using modular description. This strategy allows the reuse of tested models, improving the safety of the simulations and allowing reducing of development time. As it is discrete event formalism, it uses a continuous time base, which allows accurate timing representation, and reduces CPU time requirements. However this work focus on wireless network and it's strongly different like Wireless Sensor Network. In [8], a coupling between the NS-2 simulator and DEVS definition is showed. We observe the behavior of a sensor node's application and its environmental behaviors such as battle fields which are defined in DEVS modeling and the roles of networking protocol behaviors which are assigned to NS-2 since NS-2 has well-designed network protocol libraries. However modular aspect of all components doesn't exist and seems no easy to implement environmental scenario. On the basis of this report, we make the choice to define all components of Wireless Sensor Network using DEVS formalism.

B. DEVS formalism

Based on systems theory, DEVS formalism was introduced by Professor B.P. Zeigler in the late 70's [6], [7]. A DEVS model (atomic or coupled) can be graphically represented by a box with a set of input ports and a set of output ports. The input and output vectors are the union of all the ports of the system. An input port takes a value at the time of emission of an event attached to this port. An output port computes a value when the output function takes a value for this port.

1) Atomic Model: A modeling specification step and consequently a clear interpretation of simulation results in the real world; an atomic model DEVS presents the following structure:

$$AM = < Xm, Ym, S, \delta ext, \delta int, \lambda, ta > with :$$

- Xm the set of input ports through which external event are received;
- Ym the set of output ports through which external event are sent,
- S the set of state variables and parameters,
- δext the external transition function,
- δint the internal transition function,
- λ the output function,
- ta the time advance function.

2) Coupled Model:

Atomic models can be associated in the DEVS formalism using a multi-component model defined by the following structure:

$$CM = < X, Y, D, Md \in D, EIC, EOC, IC >$$

- X and Y are identical to those of Xm and Ym for the atomic models,
- D is the set of the names of the models occurring in the coupled model and each
- Md is an atomic or a coupled DEVS model, A coupled model tells how to couple (connect) several component models together to form a new model. This latter model can itself be employed as a component in a larger coupled model, thus giving rise to hierarchical construction.
- The couplings are described by the sets: EIC (External Input Coupling), EOC (External Output Coupling) and IC (Internal Coupling).

III. Our approach of a wireless Sensor node

In this part, we present the different atomic and coupled models descibed by DEVS Formalims These models are based of approach of node. It seems important to us to represent the different hardware components of the node. Our generic approach leads us to define their behaviour. We try to delimit the different reactions of the node units to move towards the description of a general behaviour of a sensor using a discrete event formalism DEVS. Based on our approach and object-oriented concept [1] [2] [4], we have developped a application for WSN simulation divided in four packages :

- Package PyDEVS : based on [5] a python DEVS simulator, it represents comportemental aspect and structural aspect ;
- Component Library : in this package, we can find the different components of a wireless sensor node, with atomic models and coupled models according to our approach, as described in .
- Tools Package : it represents all the models that we use during simulation : message, message generator
- WirelessSensrNetwork_Specification : it defines the network deployment by a coupling definition of nodes and rules of simulation.

The library concept allows us to develop different components and to add them in the sensor model. Our approach provides a basis for WSN simulation development.

A. Message description

We present structure of our message involving in the network :

- **Origin** defines the node which is the source of this message. Parent, this field is one of characteristic of reliable route protocol. It determines the node nearest to the basic station, the highest in routing table.
- **Sender** provides the node name which sents this message.
- **Destination** is the destination of message which has been treated by a node. The destination can be the sink or an other node.
- **Ndid** : a node can be identified by a nodeID which correspond at an identifier of a node group.
- **Type** : this field is very essential because it defines the action of the different system components : ***BSCollect*** message for Atomic Model (AM) Sensorboard has for goal to collect environmental data ; ***ACK*** message for AM Net is the acknowledgement by a node after a communication with a node ; ***WhiteFlag*** message for AM Net : network architecture signal ; ***DEAD*** Message for all models : no energy in the node or a "burned node".
- **Hop :** this field appears in our message because it is a parameter of the routing protocol Xmesh (*cf III-C2*).
- **Link** appears also like a attribute of routing protocol. It indicates the quality of connectivity between two nodes and is very important for the definition of the routing table.
- **Data :** *Temp* indicates temperature parameter coming from Sensor board.
- **Conso** is a special information message for energy cunsumption.

B. Coupled Model Sensor : definition of coupling

The model illustrated by the Figure 1 represents the coupling of our DEVS Coupled Model of sensor. This definition is important because it determines the connectivity between the model but also architecture characteristics of the future Wireless Sensor Network. Two input ports In1 and In2 and two output ports Out1 and Out2. In1 and Ou1 represent connectivity with a node and In2 and Out2 represent the conndtivity with the model of environment (*cf III-C3*). On the Figure 1 appears the central role of our MC Process.

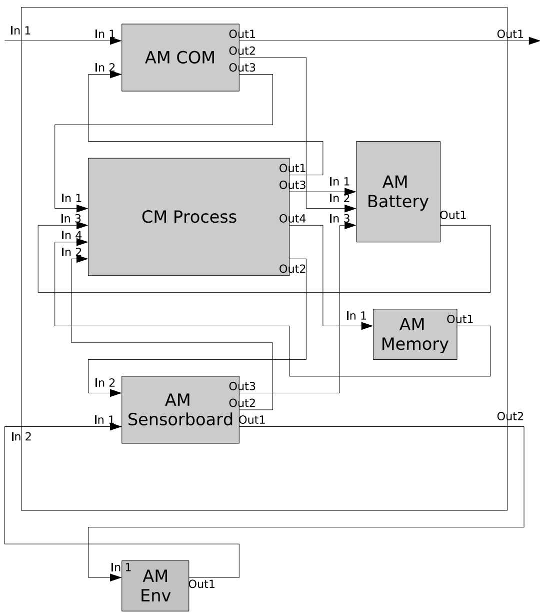

Figure 1. Coupled Model Sensor

It is important to describe the most important atomic and coupled model which compose the Coupled Model Sensor .

C. Description of component

1) Atomic Model COM: AM COM is an Atomic Model for representation of communication. The goal is to address and receive the messages of the nodes in the network. We represent only a link on input port or on output port with a different sensor node ; however it's possible to have more links depending on number of nodes connected. We define different states: ***Receipt*** for message coming on Inport1 from a node or Base Station (BS), ***Transmit*** for message going out sensor to an other node or BS, ***Busy*** is state of transition when a message is treated by MC processor, ***Free*** when there is no activity in node (node listen the channel), ***Dead*** when there is no battery in sensor or if a node is burned.

2) Coupled Model Process : CM Process is shown on the Figure 1. It is one of the most important models of our approach. All messages coming from AM COM or AM Sensorboard are treated obligatorily by this model to have routing information. AM Processor manages all messages and all components. It is difficult to represent all actions of the processor but we try to bring some solution by a generic approach. CM Process defines a simplest representation of a generic Operating System. Indeed we make the choice to decompose AM Process in three Atomic Models : AM Processor which can represent management actions of OS and the processor ; AM Net which manages the Network aspect and AM Flash which allows to modify the characteristics of CM Process (AM Flash must be considered in reusability cocncept) . These three models have only three states: **Busy** when model is in action, **Free** in sleep mode and **Dead** when there is not enough energy in the node or if the node is burned by the fire. When a message comes, AM Processor sends it to AM Net that is a model of routing management. AM Net changes routing informations in the message. AM Processor treats all messages in the model and we can exprim relative activity of node by count of each action done by AM Processor. For this model we use the characteristics of reliable route protocol (Xmesh). Indeed, estimation of link quality used to define neighbors table [13]. Link estimation is an internal value which changes according to a random definition of time. According to Xmesh protocol , one node sends its information to node with the most reliability of link. The node in receipt phase is able to insert, evict or reinforce of neighbors table. It keeps a frequency count for each entry in the table. With this algorithm, a new neighbor is inserted in the table if there is an entry with a count of zero ; otherwise the count of all entries is decremented by one and the new candidate is dropped.

3) Atomic Model SensorBoard and Atomic Model Env : The goal AM Sensorboard is to represent interactions between environment and sensors. It is an other important point of our approach. AM Env is a model as shown on the Figure 2 using environmental message to communicate with AM Sensorboard. This interconnection between these two models represents sensing action of nodes in an environment or a specific phenomenon (wildfire). When a node is sollicited to send its environnemantal data, AM Sensorboard collects these informations in the AM Env. Let us imagine a node which wants to collect its environnemental informations. It uses the AM Sensorboard. The AM Sensorboard sends a message to AM Env. AM Env receives the message and gives environmental data. According the name and the time of simulation, AM Env sends corresponding informations towards AM Sensorboard. AM Sensorboard transmits this message to CM Process. For an external communication with the other nodes, CM Process uses the AM COM.

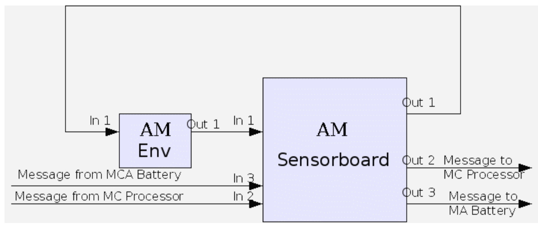

Figure 2. Atomic Model Sensorboard and Atomic Model Env

Let's see exactly the role of AM Env in the case of a wildfire.

IV. RESULTS

A. How we interpret the simulation results ?

Each node has two roles : sender and router. Each node sends periodically its environemental informations using routing protocol to reach the BaseStation. In our first case of simulation, we use a Wireless Sensor Network with 60 nodes as shown on the Figure 3. When there are not arrows between two nodes, it means there are not communications because the sensors are too much distants. The sensors are disposed like a grid, mesh manner, where each node can't have more than four neighbors.

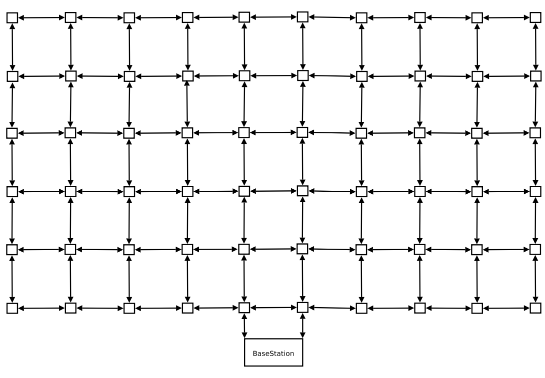

Figure 3. Wireless Sensor network with 36 nodes

Our DEVS application collect only the data which have reached the BaseStation. We show on the TABLE I the table results which is analyzed.

Parent	timeLast(sec)	TEMP (Celsius)
node1	0	12,5
node2	0,8	13,1
node3	1,2	12,5
node1	2	13,2
node5	2,8	12,6
node4	3,2	12,8
node6	4	12,3
node8	4,4	13
node1	4,8	12,3
node2	6	12,2
node3	6,4	12,4
node1	6,8	12,3
node7	8	13,4

Table I
EXAMPLE OF DATA COLLECTED ON THE BASESTATION

We can see the name of the node which has send the data, the time of arrival (in seconds) on the base station for each message and the temperature value (celsius). For better understanding, we don't show a table of results because we prefer to represent the temperature value in using a network representation like as shown on the Figure 3. A black zone represent the impact zone of wildfire on wireless sensor node.

B. *Wildifre Scenario : basis reflexion*

We want to analyze the impact of wildfire on Wireless Sensor Network. To represent a fire, we define in the Atomic Model Env, the node which will receive during the simulation a special informations of AM Env. The special message is an important value of temperature. When AM Sensorboard receipts this value, it detects a value superior at a fixed threshold (threshold : 70°C) and changes its current state in "DEAD". "DEAD" is a critical state, propagated in the node, with goal to represent a "burned node" like illustrated on the Figure 4.

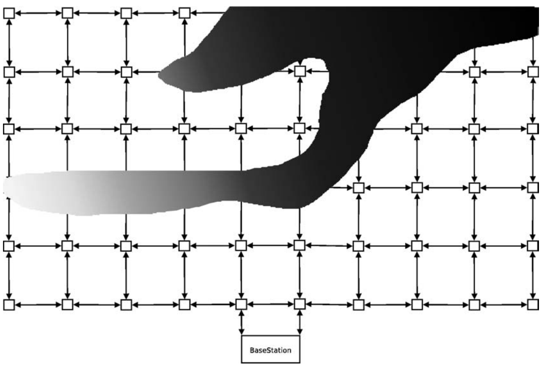

Figure 4. Representation of nodes in contact with wildfire

A "burned node" can't communicate with the others node during the rest of simulation. In this critical phase, the "burned nodes" don't appear any more in the table of results and don't play the router role for the other node communications. During the simulation , we alert the using of the Xmesh protocol [13], implemented in AM Net model. The Figure 5 represents the results interpreted according to the results table of BaseStation after 10 minutes of simulation. It appears clearly that there is a great difference between network area and BaseStation visualization. This error represents the loss of connectivity between the nodes.

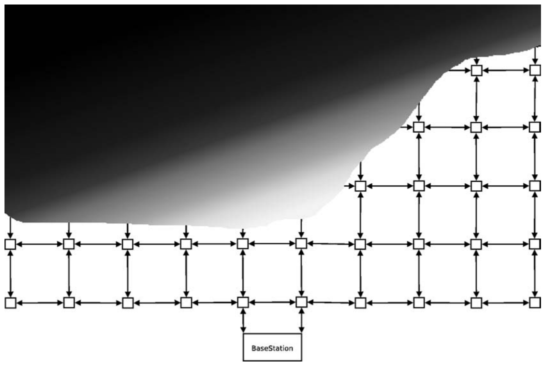

Figure 5. Representation on the BaseStation

In this precise case where the environmental phenomenom can destroy the system, WSN can't provide reliable informations about fire evolution after a certain time. Indeed the nodes which are "DEAD" state can not play the router role and the structure of the network is clearly defective. A significant number of messages is lost. According to the BaseSation informations (table results), we don't know where is localized the fire and it isn't possible to follow its evolution only in the intact area. This aspect is very important because it can define the firemen actions. A burned area on BaseStation observed on the Figure 5 doesn't represent the reality. The time of arrival of the most distant node of the base station is 375 seconds. This scenario shows one of the limit of wildfire monitoring using a Wireless Sensor Network due the default of WSN architecture. Indeed the deployment of WSN as shown on the Figure 4 is not effective because one BaseStation is not sufficient.

C. *Effective deployment*

1) Complex grid deployment: We show in our basis reflexion that the wireless sensor network deployment is essential to monitor wildfire. To illustrate this idea, we use the same number of sensor node however the network is divided in four small networks as showed on the Figure 6.

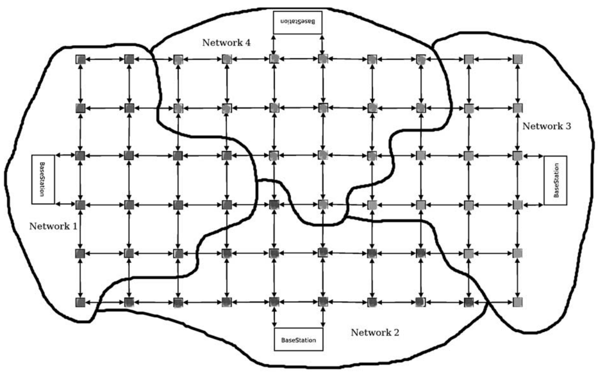

Figure 6. Deployment of 4 small WSN

On the Figure 7 we observe the same scenario of wildfire that the Figure 4. We see that the Network 4 is in critical phase where the nodes can't communicate with the BaseStation. This case is partially identical on the Network 1 however a part of network can transmit again some informations.

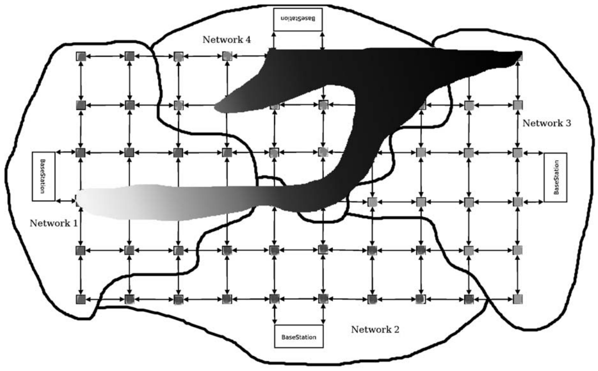

Figure 7. Analysis of results of 4 small WSN in wildfire conditions

On the Figure 8, we observe the results on each BaseStation and the global results. We see that the representation is more accurate that a simple grid deployment. Indeed, the large dark zone observed on the Figure 5 is reduced. The representation that we can have according to results the table of BaseStations is more accurate however there is always some dark zones. The time of arrival of the message is reduced. Indeed we can observe in all networks, a maximum time of arrival at 100 seconds.

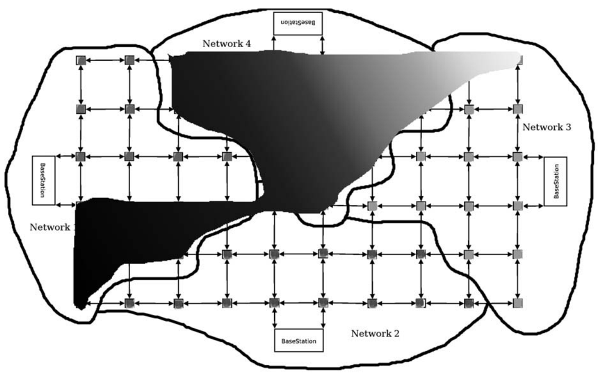

Figure 8. Global representation of wildfire on different BaseStations

2) Simple and complex Circle deployment : In the focus on deployment strategies, we try to evaluate not a grid architecture but a circle deployment with 69 nodes around one BaseStation. We inject a wildfire scenario identical that the previous studies as showed on the Figure 9.

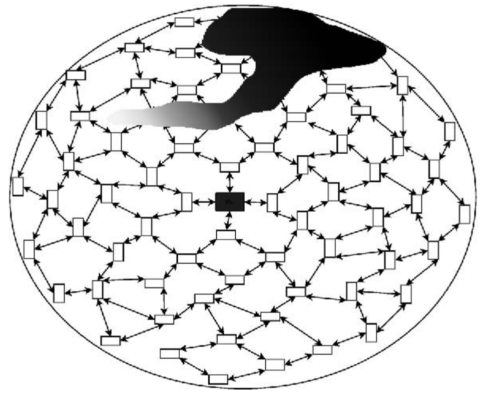

Figure 9. Simple circle deployment of WSN

In the results table of the BaseStation, all nodes not concerned by the wildfire destruction have transmetted the results. We have the exact representation of fire location. We can explain these results by wireless sensor network deployment. Indeed the communication between the nodes can exist because there is always some router around their positions. The informations can be always diffused. However, the time of arrival of messages increased in an important way. The messages from the nodes around fire don't use a direct way to reach the BaseStation. The used way to reach the BaseStation requires more nodes and consequently increases the time of arrival. The informations arriving on a BaseStation is distorted considerably on the time level. We can observe a difference a time of arrival superior with 540 seconds.

To reduce this time, the same methodology use for the simple grid deployment is applied. We have the same number of node however we reduce the network in four small networks like as shown on the Figure 10.

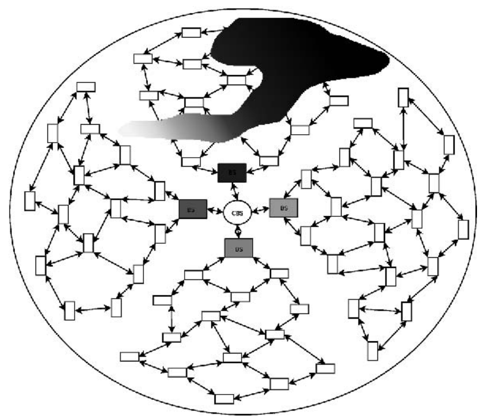

Figure 10. Complex circle deployment with four BaseStations

We observe four networks. The wildfire impact is clearly identified on a Wireless Sensor Network, on the top of the Figure 10. The time of arrival is reduced for each sub-networks and the maximum identified time of arrival of message on a base station is 118 seconds.

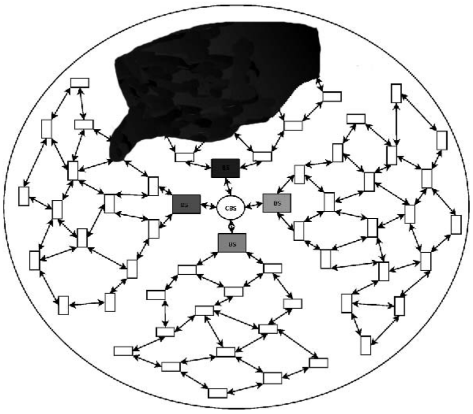

Figure 11. Analysis of the results of a complex circle deployment

The impact of wildfire scenario on WSN as showed on the Figure 11 with a complex circle deployment can be interpreted in two ways :

- a complex circle deployment with four small networks is more accurate in wildfire location than a simple grid or a complex grid deployment however this architecture is not more accurate than a simple circle deployment.
- the arrival time of each message in a complex circle deployment is less important that a simple grid deployment.

The study of wildfire scenario under different WSN deployments bring some responses :

- the WSN deployment plays an imporant role in destroying phenomenon monitoring ;
- it seems more accurate to use several small WSNs than a greater WSN ;
- a circle deployment is more accurate than a grid deployment ;
- the robustness of the environmental monitoring tool is increased with several small WSNs ;
- the time of arrival of the messages is increased with the number of nodes ;
- the mesh deployment concept must concern the nodes but also the Base Stations deployement in wildfire phenomenon ;

Wireless Sensor Network is able to observe the evolution of a phenomenon and not only to detect the birth of condition. In wildfire conditions, we see that it is important to increase the capacity of communication to provide reliable informations to firemen and a deterministic can be often failing.

V. Conclusion and Future Work

This article proposes a study of Wireless Sensor Network in wildfire conditions. This approach is based on the DEVS formalism for the modeling and the simulation of complex discrete event system. We have demonstrated the limit of a deterministic deployment design of Wireless Sensor Network. We have confirmed the hypothesis that it is more reliable using several small WSNs than a great WSN to follow the evolution of destroying phenomenon. We have also demonstrated that circle deployment is more accurate than a grid deployment. Our work wants bringing some directions to understand behavior of Wireless Sensor Network. The time of arrival of each message is very important in wildfire case because it determines the firemen action. The future works aim to validate these theorical approachs by a test in real conditions. The goals are to develop sensors protections to reduce the wildfire impact on the WSN and explore the propagation time of the fire front.

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VII. Biographies

Thierry Antoine-Santoni maintained his doctoral thesis in 2007 at the University of Corsica. His work focuses on modelling and simulation of complex systems based on the DEVS formalism developed by BP Zeigler, Wireless Sensor Network and Bioinformatic.

Jean-François Santucci is Professor in Computer Sciences at the University of Corsica since 1996. His main research interests are modeling and simulation of complex systems. He has been author or co-author of more than 100 papers published in international journals or conference proceedings.

Emmanuelle de Gentili maintained her doctoral thesis in 2002, Assistant Professor at the University of Corsica since 2004. His work focuses on modelling and simulation of complex systems based on the DEVS formalism, fuzzy logic and dynamic systems.

Bernadette Costa is Professor in Electronics at the University of Corsica since 1989. His main research interests are electronics, signal processing and acoustics. She has been author and co-author of many papers published in international journals or conference proceedings.