GIS Based Deployment Strategies of Wireless Sensors Networks for Forest Fire Surveillance

Wassim D. Katerji, Hoda W. Maalouf

Department of Computer Science, Notre Dame University
Zouk Mikael, Lebanon

wkaterji@ndu.edu.lb

hmaalouf@ndu.edu.lb

Abstract **– The objective of this paper is to demonstrate the usage of Geographic Information Systems (GIS) in optimally distributing a set of permanent stationary sensors to ensure the reliable functioning of a wireless sensors network (WSN) in the case of forest fires. Once a fire occurs, an additional set of sensors are air-dropped over the area. Both stationary and air-dropped sensors will form a network that will transmit back to the base critical real-time information. Collected information, such as temperature, wind direction, humidity, pressure and pollution level, will enable the fire fighters to accurately assess the situation before heading on-site. A GIS based, as well as a terrain and obstacle aware procedure is presented in this paper which enables the optimal distribution of the stationary nodes and permits the calculation of several performance parameters such as the network connectivity in 2D and 3D, the total number of generated sub-networks. The proposed procedure is based on the minimum surface curvature, the maximum transmission distance between two nodes, and the total number of deployed nodes. These parameters are related to the hardware used and to terrain nature of the area under study. Simulation results have shown enhancements in specific combination between the total deployed nodes, and the minimum surface curvature. The simulation was realistic by adopting a real forest data, which was possible by the capabilities of GIS to store, process and display a big amount of geographically-positioned data.**

Keywords **– Geographic Information System, Wireless Sensors Network, Network Connectivity, Forest Fire Surveillance.**

I. INTRODUCTION

Forest fire early surveillance and detection systems were based on cameras, infrared sensors and satellite systems. Such systems were lacking the ability of real-time data collection and support. Wireless sensor networks (WSNs) came in hand and helped in collecting and providing real-time data on temperature, wind direction, humidity, and pressure and pollution level at the different locations of the forest fire. The collaboration between different fields of geographic information science and WSNs can provide appropriate techniques and tools that will enhance the capabilities of fire prevention, early detection, efficient surveillance, efficient spread control, and fast termination of such hazards [1].

In the majority of WSN researches, the network model is assumed unobstructed/flat areas, where there are no physical obstacles preventing the different nodes from communicating with each others. In order to be more realistic in studying and applying WSNs, especially in hostile and harsh environments, physical obstacles and terrain irregularities that prevent effective signal propagations should be taken into consideration while designing the deployment of the sensors and the routing protocol, as it directly affects the overall network reliability and durability [2, 3].

Geographic Information System (GIS) will be extensively used in this research as a tool for storing all the necessary data from various sources and structures, performing data manipulation, analysing and visualizing the results in both 2D and 3D.

This paper is divided into 8 sections. Section 2 presents previous work related to the study. Section 3 studies the main design requirements of our system. Section 4 gives some details about the usage of GIS. Section 5 explains the methodology in solving the problem in-hand which involves 3 different sub-procedures. Section 6 simulates the resulting solution and analyses the output. Finally, section 7 summarizes the paper and suggests some potential future work.

II. RELATED WORKS

Geo-information Technologies which include Geographic Information Systems (GIS), Remote Sensing (RS) and Global Positioning System (GPS), are being used to prevent and sometimes even control the damages caused by natural hazards, including wildfires, with the aim to prevent those hazards from becoming real disasters. In special, GIS provides a powerful tool for storing, managing, analysing and displaying geographically distributed data that can be used for the mentioned objectives. In fact, GIS is used in natural disaster management at the three different stages [4]:

- Before the disaster, GIS is mostly used in hazard identification, disaster prevention and mitigation plans, emergency preparedness, etc.
- During the disaster, GIS and RS can help in effectively and promptly respond to such disaster, through the use of spatial analysis, hazard simulation, and data visualization.
- After the disaster, GIS is used to store and analyse data at the different post-disaster period: relief, rehabilitation, and re-construction.

In order to cover the forest under study, different deployment strategies of the wireless sensors can be applied such as static ground deployment and air-dropped deployment. In the case of static ground deployment, the location of the sensor nodes are well known since GPS units are usually used to determine the exact coordinates of each placed sensor. However, this deployment procedure could require a large load of man-power work, in order to manually place each node, especially in forests spreading over large areas, where thousands of sensors are needed. Keep in mind that some locations inside the forest could be dangerous or impossible to reach, thus the failure of such deployment at those locations [5]. In the case of air-dropped deployment, sensors are deployed from aircrafts. Each sensor will become a projectile that will follow a path from the aircraft till it hits the ground. Once it hits the ground, it becomes a static node in the used WSN. Despite the ease and speed of this deployment strategy, we can never ensure a uniformly distributed network over the desired area since the low weight of the sensors, wind speed and direction can play a significant role in shifting the direction of the trajectories. Moreover, air-dropped deployment does not take into consideration the terrain surface beneath it, which will increase the randomness of the distribution

Hence, static deployment cannot be considered as a practical way, when it comes to a broad area of coverage. However, it is very efficient to adopt especially when it comes to a limited amount of nodes to be placed. On the other hand, air-dropped deployment is considered relatively more practical, at the expense of low reliability due to the inability to control the trajectories of the sensors. In this paper, a combination of both static and air-dropped deployment methods will be proposed.

87The main objective of this research is to combine these two different deployment strategies when using WSNs for forest fire surveillance, by presetting stationary sensors on critical locations along an irregular and obstacle-aware terrain, in order to guarantee the reliable functioning of the WSN within that area, when needed. Although it could not be the only research project choosing such combination, it can be considered as the first research paper that uses the static deployment at first, then applies the air-dropped deployment, as the opposite order used by the other researches [2,5].

III. System Design Requirements

In order to have a reliable and highly available WSN, nodes distribution plays an important, yet a difficult task, at the physical layer of the network. As discussed previously, it is nearly impossible to guarantee the position of each sensor. Even more, after the initial positioning of the nodes, they might get displaced due to natural forces. What remains highly important is to ensure that such random networks are connected. In order to test the design of the physical layer, an emulator will be implemented in this paper that will allow signal propagation to be modelled in different ways:

- Extensively using statistical models of signal propagation.
- Replaying the traces of the observed signal propagation.
- Analysing the behaviour of the controlled signal propagation artificially, before implementing in real.

In order to be able to systematically test and analyse the artificially generated models, there is a need to have a set of quality metrics that will be used to evaluate the system by comparing it to them. These metrics need to be set based on the network hardware available, the nature of the implementation environment, and the desired application that the network will be used for [2, 6, 7]. These metrics are: the minimum surface curvature, the maximum transmission distance between two nodes, and the total number of deployed nodes.

IV. GIS in Forest Fire Detection

GIS will be used as a tool to model the system and the environment in which it will be implemented. In fact, GIS will enable us analysing the connectivity of the nodes, detecting poorly covered areas and assessing the overall availability and reliability of the system. The usage of GIS in this project is considered in the before-disaster stage, whereas the resultant solution, once implemented, could be used during the disaster stage [4]. Moreover, 3D GIS will be employed to accurately model and visualize the results of this research. In particular, we will utilize ESRI ArcGIS 9.2 software package. ArcGIS was chosen among other GIS software packages for its high capabilities in storing, processing and visualizing geographic data, its big library of geoprocessing and spatial analysis functionalities, as well as its ability to be customized and extended with additional developed tools.

In order to accurately analyse the data, it needs to be modelled in 3D, so that the obstacles and the terrain are well identified. An obstacle represents any object falling in the line of sight (LOS) between any two nodes, and preventing them from communicating with each others. Different scenarios will be simulated to assess the efficiency of the implemented technique. Enhancement of the network reliability will be analysed after static (and accurately) deployed nodes are added to the network, in order to come up with a proper trade-off between required reliability versus additional budget.

The forest under study in this paper is a natural reserve situated in northern Lebanon. This forest is spread over 5 km^2 and has a varying mountainous surface, ranging from 860 to 2350 m. above sea level. However, we should note that the proposed model can be applied to any area for study, provided the availability of the necessary data, as explained in the next section.

V. Procedure

This section will describe the used procedure to solve our problem; that is, given a forest under study, where should the static sensors be placed so that the remaining air-dropped sensors would form together with these already installed nodes a WSN that is reliable and durable. Our proposed procedure is divided into 3 sub-procedures as follows:

1. Determining the number and the locations of stationary nodes that will be needed to enhance the connectivity and reliability of the potential network.
2. Defining the physical obstacles, their effects and expansion of a generalized multi-path model.
3. Analysing the connectivity between the air-deployed nodes based on the possibility of physical

communication between them, on their own; and, with the assistance of the placed stationary nodes.

We should note that ArcGIS is an all-purpose GIS software package, and not specialized in WSN. The proposed procedure is developed under ArcGIS using Modelbuilder and Python Script. Modelbuilder is a visual tool that enables to automate a set of tools, whether built-in or custom developed, to run sequentially and share parameters. Python is a programming script that is supported by ArcGIS to write new tools. While ArcGIS also supports VB Script and Java Script. Python was chosen to be used as it the most supported script in ArcGIS.

A. *Stationary Node Determination*

The objective of this sub-procedure is to estimate the position of possible critical locations on the provided surface, where pre-existing stationary nodes will play an important role in enhancing the connectivity of the WSN. The decision is based on peaks having a minimum defined curvature value. Taking into consideration that the stationary nodes will be placed in natural reserve, they will be attached on trees and will be assumed to be as 3 meters above the ground.

The current sub-procedure requires several input data, namely a raster layer containing the digital terrain model (DTM) of the area under study, a vector polygon layer containing the boundary of the area under study, the minimum required curvature (C_{min}) and *the* maximum transmission distance between two nodes (D_{max}).

This sub-procedure can be summarized as follows:

- Create Flow Direction from *DTM*, named *FlowDir*. Flow direction is a tool mostly used in hydrology that determines at each point the direction toward the highest downward slope. The flow direction is created as a prerequisite for the next step only.
- Create Flow Accumulation from *FlowDir*, named *FlowAcc*. Flow accumulation is also used in hydrology to calculate at each point the total accumulated water drops starting from the peaks of the mountains. This tool is used in order to depict the peaks of the mountains, where the peaks are the locations with zero accumulations.
- Select peaks from *FlowAcc where FlowAcc = 0*, named *AllPeaks*
- Create curvature from *DTM*, named *Curvature*.
- Select curvatures higher than the minimum provided threshold, where *Curvature* $\geq C_{min}$, named *HighCurv*.
- Combine *AllPeaks* and *HighCurv*, named *PeakCurv*. Combining information from different layers based on the same location. This is an example of overlay analysis, which is one of the three major types of analysis in GIS (Overlay, Proximity and Network).
- Remove unnecessary peaks that are too close to each others (i.e. closer than D_{max}). In this case, the highest peaks are kept since they have broader range of visibility.

The resulting output of this procedure is called *Peaks* which is a vector point layer containing the filtered peaks with their actual *(X, Y, Z)* coordinates (Fig. 1). *Z* represents the ground elevation above the sea level where a specific node resides.

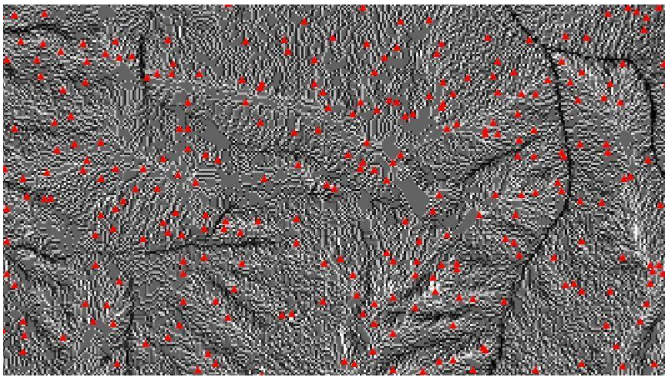

Fig. 1. Peak Stationary Nodes

B. *Obstacle Definition*

This is a generalized model, where in reality more complex signal propagation occurs. However the main objective of this proposed one is to check for open corridors in the terrain surface where the signal can propagate to reach the destination. Two nodes can directly communicate with each other if and only if the distance between them is $\leq D_{max}$. In cases where there is no line of sight (LOS) between two nodes [8], multi-path transmission needs to be adopted as follows:

- For simplicity purpose, the multi-path will be generalized into a single refraction only.
- Unaware of the physical and morphological nature of the obstacles, the refraction absorption of the signal energy cannot be accurately estimated and is beyond the scope of this paper. However, this absorption will not be ignored and shall be represented as an estimated absorption factor κ, where $0 \leq \kappa < 1$. For the remainder of this study, it is assumed that $\kappa = 0.95$.
- In order to reach the destination, the total trajectory of the signal should not exceed the maximum allowable distance between the nodes, D_{ref} ,where $D_{ref} = D_{\max} \times \kappa$
- Multi-path refraction shall be tested in three directions: above, to the right, and to the left of the obstacle.
- The refraction angle β in either three directions is calculated as $\beta = ArcCos(d/D_{ref})$, where *d* is the distance between the two nodes *i* and *j*.

The objective of this sub-procedure is to find the coordinates of the three extreme refraction locations for any given two nodes. First, the upper middle point *t* is calculated as (Fig. 2), then, the left *l* and right *r* middle points are calculated as (Fig.3):

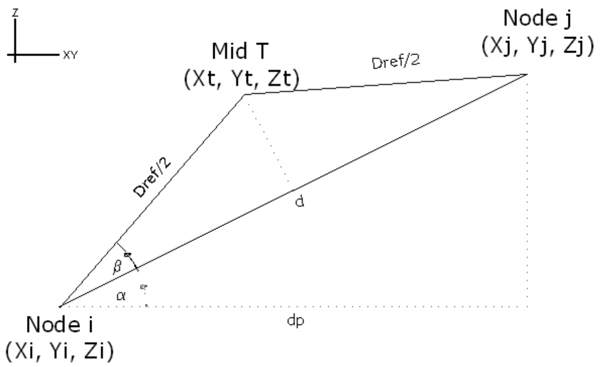

Fig. 2. Positioning top refraction point

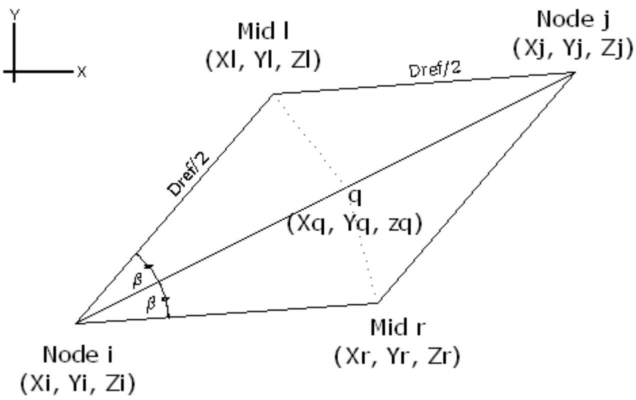

Fig. 3. Positioning left and right refraction points

The resulting output of this sub-procedure is a table named *CoordinatesTable* that contains for each pair of nodes the coordinates of nodes *i* and *j*, the refraction angle *β* and the coordinates of the top middle *t*, the left side *l* and the right side *r* points.

C. Network Connectivity

After computing the edge points of the multi-path model, the objective of this sub-procedure is to check the physical connectivity of the nodes with each other and evaluate the overall level of the WSN connectivity, for both the air-dropped nodes alone, and with the assistance of the stationary ones.

The required inputs for this sub-procedure are the *DTM* raster layer, the vector point layer (called *Nodes*) containing the deployed nodes, the vector point layer *Peaks* containing the stationary nodes (see 4.1) and the table *CoordinatesTable* (see 4.2).

This sub-procedure can be summarized as follows:

1. For each pair of nodes *i* and *j* and given the intermediate points (*t*, *l*, and *r*), create the following edges as 3D vectors: $\vec{ij}$, $\vec{it}$, $\vec{tj}$, $\vec{il}$, $\vec{lj}$, $\vec{ir}$ and $\vec{rj}$. In Fig. 4 $\vec{ij}$ is shown in green; $\vec{it}$ and $\vec{tj}$ are shown in yellow; $\vec{il}$, $\vec{lj}$, $\vec{ir}$ and $\vec{rj}$ are shown in magenta.
2. Calculate the *LOS* of the above calculated edges. LOS is a function in GIS that checks the direct visibility between the 2 vertices of each line edge with respect to a given DTM. The result of this tool is a set of line segments classified as visible or non-visible.
3. Select and delete all the edges that are non-visible.
4. Aggregate for each pair of nodes *i* and *j* all the possible connections between them, in term of availability of LOS and/or multi-path.
5. Summarize the overall network in term of the total number of connected nodes vs. unconnected nodes and the total covered area vs. uncovered area.
6. Append stationary sensor nodes to the existing nodes, and repeat steps 1-5

The resulting outputs of this sub-procedure are a vector polylines layer *Edges1* containing the connected edges between the nodes, a vector polylines layer *Edges2* containing the connected edges between the nodes after including the stationary ones, a table *Summary1*containing the summary of the overall network and a table *Summary2* containing the summary of the overall network after including the stationary nodes.

Fig. 5 shows a sample comparison between assumed unobstructed 2D connections between the nodes and the actual 3D terrain-aware connections, where connected nodes are shown in green while the unconnected ones (while being assumed connected in 2D) are shown in red.

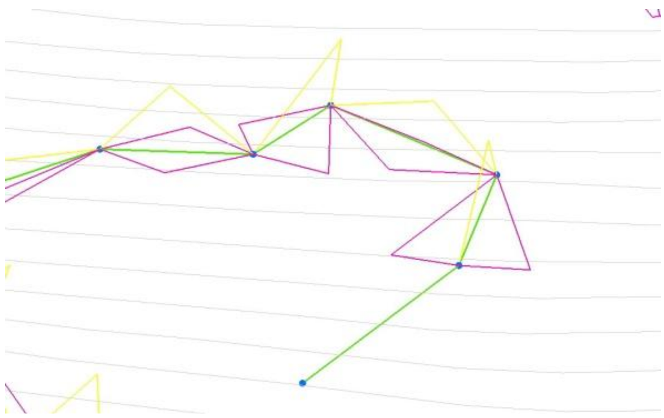

Fig. 4. 3D view of Multi-path model

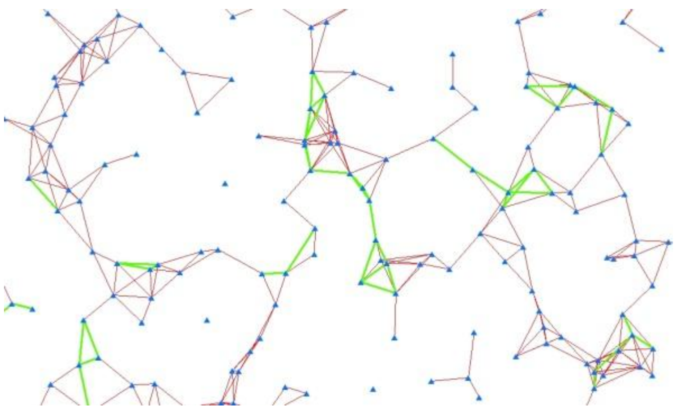

Fig. 5. Nodes 2D versus 3D connectivity

D. Summary

To sum it all, given a WSN defined by a total number of nodes to be deployed *N*, a maximum transmission distance D_{max} and a minimum terrain curvature C_{min}, our proposed procedure gave the following results:

- The overall connectivity of the deployed nodes.
- The enhanced connectivity after including the stationary nodes to the network.
- The total required stationary nodes N_{sta} and their positions.
- An evaluation on the level of network connectivity enhancement with respect to the additional stationary nodes cost.

VI. Simulation Results

This section presents simulation results of our proposed procedure, based on 48 simulations where the input values for the WSN under study are the combination of:

- The maximum transmission distance $D_{\max} = 100m$,
- The minimum terrain curvature $C_{\min} = [5,16]$,
- The total number of sensor nodes to be used $N = 600, 850, 1050, 1850$

The main simulations results are summarised in the following 3 graphs. Note that each curve in the graphs represent one of the total number of sensor nodes, presented as a percentage of the average distance between two nodes, with respect to the maximum transmission distance:

- Fig. 6 shows the reduction rate of total sub-networks in terms of the chosen minimal curvature. Note that in cases of 90% and 75%, there are combinations that increase the number of sub-networks instead of reducing it. Those combinations are to be strictly avoided.

- Fig. 7 shows the additional required cost, expressed in the rate of additional node, in term of the chosen minimal curvature. Setting the criteria that the additional nodes shouldn't exceed 50% of the deployed ones, limits the decision on the minimum curvature to adopt for the various cases.

- Fig. 8 combines Fig. 6 and Fig. 7, to show the enhancement in the network, expressed in the reduction rate of sub-networks, in terms of additional cost, expressed in rate of additional required nodes. Solutions that reduce the number of sub-networks at an additional cost less than 50% are to be adopted solely.

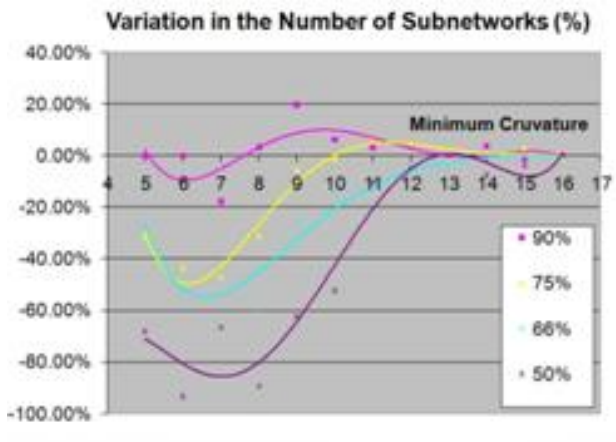

Fig. 6: Reduction in Sub-Networks

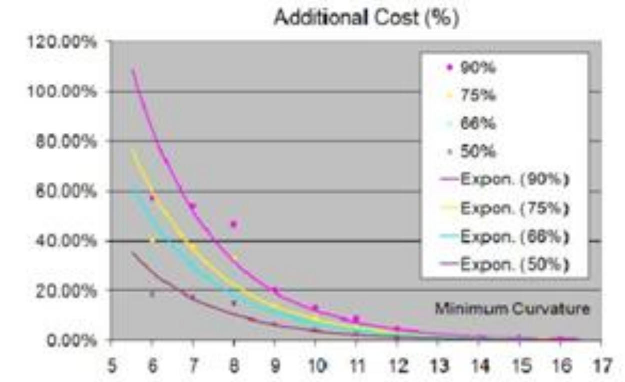

Fig. 7: Additional cost in terms of nodes

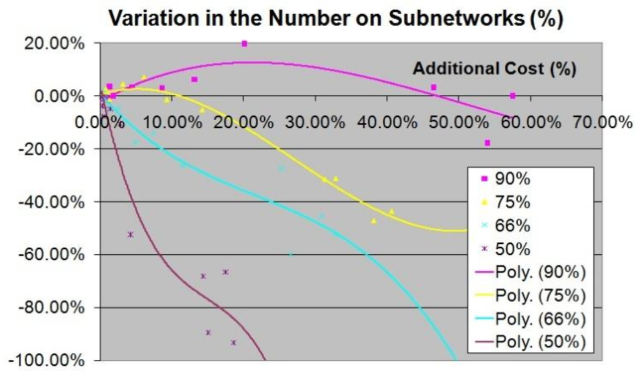

Fig. 8: Enhance VS. Cost

The analysis shows that not all the simulations resulted in enhancing the network, and some of those resulted with an enhancement, were at a very high cost. Beneficial results are restricted into the decision of the average distance for deploying the nodes, expressed as rate of the maximum distance. The rates of 50% and 66% were beneficial, whereas 75% and 90% were not.

- Adopting 90% as the average distance is only beneficial if the cost exceeds 50%, thus this option is not recommended to be used at all.

- Adopting 75% as the average distance is only beneficial if the cost exceeds 15 %, thus having a range of acceptable cost between 15% and 50%
- Adopting 66% or 50% return beneficial results since their cost percentage values are below 50%.

VII. CONCLUSION

Throughout this paper, we have depicted, using GIS, the positions of critical locations that might create obstacle to an air-deployed WSN when used. The aim of this analysis was to place additional stationary nodes, prior to the air deployment, in order to enhance the connectivity of the later network. The depiction of those critical points was calculated based on three inputs: a digital terrain model (DTM) that represents the surface model of the terrain under study, the maximum transmission distance allowable between two nodes, and a minimum terrain curvature that will create an obstacle.

A major task to be considered as a future work is the determination of a more detailed and realistic signal propagation model, and to be tested with a more detailed terrain model, which includes man-made structures along with detailed natural features.

REFERENCES

[1] Y. Li, Z. Wang, Y. Song, *"Wireless Sensor Network Design for Wildfire Monitoring"*. 2005

[2] I. Chatzigiannakis, G. Mylonas, S. Nikoletseas, *"Modeling and Evaluation of the Effect on Obstacles on the Performance of Wireless Sensor Networks",* Proceedings on the 39th Annual Simulation Symposium (ANSS'06), IEEE, 2006.

[3] M. Younis, P. Munshi, G. Gupta, S. Elsharkawy, *"On Efficient Clustering of Wireless Sensors Network"*, Proceedings on the 2nd Workshop on Dependability and Security in Sensor Networks and Systems (DSSNS'06), IEEE, 2006.

[4] Md Mahbubur Rabb Meena, *"Using Geoinformation Technology to Develop a Vulnerability Assessment Model in Natural Disaster-Prone Areas"*, Daffodil International University Journal of Science and Technology, Volume 1, Issue 1, July 2006.

[5] N. Markatos, V. Vescoukis, C. Kiranoudis, P. Balatsos, "Towards an Integrated System for Planning and Decision Support in Forest Fire Management", Wildfire 2007.

[6] A. Ibrahim, M. Ismail, K. Jumari, T. Sieh Kiong, *"Simple Method for Outdoor LOS Propagation Model Using Ray Tracing Tools"*, Journal of Applied Sciences 6(12), pages 2652-2656, 2006, ISSN 1812-5654.

[7] E. Onur, C. Ersoy, H. Delic, *"Quality of Deployment in Surveillance Wireless Sensor Networks"*, International Journal of Wireless Information Networks, Vol. 12, No. 1, January 2005.

[8] J. Li, L. Andrew, Ch. Heng Foh, M. Zukerman, M. Neuts, *"Meeting Connectivity Requirements in a wireless Multihop Network"*, IEEE Communication Letters, Vol. 10, No. 1, January 2006