| BULETINUL Universităţii Petrol – Gaze din Ploieşti | Vol. LXIII No. 2/2011 | 79 - 88 | Seria Tehnică |
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# Pipeline Infrastructure Monitoring Using Wireless Sensor Networks

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## Abstract

*This paper present some results of the personal scientiffic doctoral research regarding the monitoring of transportation pipelines of oil and gas using wireless sensors networks.*

*Wireless sensor networks is a new area of research which is rapidly growing due to the development of new technologies in inexpensive sensors. These electronic devices have increased capabilities in processing speed, memory,communication and networking. Such sensor networks have a vast amount of applications including environmental monitoring, military, ecology, agriculture, inventory control,robotics and health care. This paper discusses the issues and challenges in the use of this new and very promising technology in the protection and monitoring of the critical and essential infrastructures of pipelines carrying oil, gas, water, and other important resources.*

*The paper presents a topological and architectural model that can be used to provide this monitoring and control functions. The model includes an overview of networking and routing protocols that can be used to provide the necessary communications. In addition, the paper provides discussions and recommendations concerning network reliability and the use of different wireless sensor technologies.*

**Key words:** *wireles sensor nets, pipeline oil and gas transportation monitoring, topological and architectural models.*

## Introduction

Wireless sensor networks captured the attention of a great number of researchers from the moment when in 1999 Business Week review has announced the 21 st technologies most important for the 21 st century[1].

Among them there is the technology based on wireless sensors networks , architecture which is composed of microsensors of unique use that could be implemented outdoor on soil , in the air, under water, in indoor buildings, on the vehicles, on humans bodies, or an animals bodies. WSN have a topology based on high density of distributed sensors along the pipeline and are organized in clusters (groups) of nodes which control some portions of the pipeline imposing a large scale of safety by colaborating each other in order to ensure a good function of the whole ensemble [2].

The energy crisis determined the acceleration of development of a lot of investments in oil and gas industry and the investments in WSN represents a key domain in the whole chain for the supply with oil and gas. The transportation of oil and gas is usually realised by pipeline mounted on fields which offers severe weather conditions fact which make difficult the verification of the status of the pipelines along all the direction of thousand of kilometers.In the table 1 there are presented some of the most famous pipeline of that kind.

**Fig.1.** The pipeline for gas transportation monitored drom WSN (source: Chris Sauerwald, http://www.flickr.com/people/afterfate)

**Table 1.** Oil and Gas Pipelines Examples [4]

| | |
|---|---|
| **Trans-Alaska** | Length=500 km<br>Transports oil from North Alaska to maritime ports and then with ships to cities of the USA. |
| **Russia - China** | Length=600 km; transports oil from Siberia to China |
| **Russia - from Baltic Sea** | Length=890km;<br>transports natural gas to Sweden , Norwey, Germany. |
| **Trans-Afganistan** | Length=2000km; transports natural gas from Turkmenistan, through Afganistan, towards Pakistan and India |

The attention regarded to the investments in monitoring the pipelines of oil and oil products and natural gas is determined by the danger which represents the accidental leaks from pipelines toward the environment and the enormous looses in case of accidents. For understanding the interest of researchers regarding the implementation of WSN for monitor the pipelines for oil, oil products and natural gas transportation in table 2 there are presented some examples of the consequences of recent accidents. It is obvious that the probability of appearance of the accidents can be much minimized by monitoring and close control of the state of the infrastructure and parameters of the transport from pipelines.

The transport safety depends in a great number of the safety of the monitoring system and control.The ideeas presented justify the research orientation regarding the increase the safety of feeding the nodes with energy; this fact is important for the safety in functioning the whole snesors network destinated for monitoring and surveillance of the transportation systems through pipelines from the extraction point to the storage areas and processing areas.In table 3 there are presented some of the advantages of the WSN for pipeline protection.

For understanding ther interest of the researchers for WSN implementing for pipelines monitoring for oil and gas transportation in table 2 are presented some of the consequences of recent accidents.

**Table 2.** Consequences of some recent accidents on the transport pipelines of oil and gas [5]

| | |
|---|---|
| **1989** | ***Sparks from two passing trains*** detonated gas leaking from an pipeline near ***Ufa, Russia***. Up to 645 people were reported killed. |
| **1998** | ***Jesse pipeline explosion*** the ***Niger Delta*** in ***Nigeria***, a petroleum pipeline exploded killing about 1,200 villagers. |
| **1999** | A pipeline rupture in a ***Bellingham, Washington*** park led to the release of 277,200 gallons of gasoline. The gasoline was ignited, causing an explosion that killed two children and one adult. |
| **2000** | Natural gas pipeline rupture and fire near ***Carlsbad, New Mexico;*** this explosion and fire killed 12 members of the same family. |
| **2004** | A major natural gas pipeline exploded in ***Ghislenghien, Belgium***, killing at least 24 people and leaving 132 wounded. |
| **2006** | An oil pipeline ruptured outside ***Lagos, Nigeria***. Up to 200 people may have been killed. |
| **2007** | A propane pipeline exploded near ***Carmichael, Mississippi***, Two people were killed instantly and an additional four were injured. Several homes were destroyed and sixty families were displaced |

Pipelines can be the target of **vandalism, sabotage**, or even **terrorist attacks**. In war, pipelines are often the target of military attacks, as destruction of pipelines can seriously disrupt enemy **logistics**.

Obviously, the likelihood of accidents can be significantly reduced, through monitoring and strict control of the state of infrastructure and process parameters of the pipeline transport system.

Transport safety depends largely on the safety monitoring and control system. Taking into consideration all the above, the focus of our scientific research on increasing the security of energy supply nodes is justify because this affects the operational safety of the entire sensor network systems for the monitoring of pipelines transport systems of oil and gas from extraction areas to the storage or processing areas. In Table 3 shows are some of advantages of the WSN for pipeline protection**.**

**Table 3.** Advantages of the WSN for pipeline protection [3]

| | |
|---|---|
| ***Network Deployment*** | sensors is greatly reduced due to the lack of the need for laying down costly wiring which is also much more involved to connect requiring specialized expertise. |
| ***Network maintenance process and personnel*** | the maintenance personnel need very little expertise and they do not need to have specific engineering or programming skills, which reduces the labor cost that is required. |
| ***Reliability and Security*** | many security provisions can be employed to further enhance the security and robustness of the network against many types of attacks. |

# Topology-Architecture Model of WSN

A pipeline monitoring and inspection system has a long list of tasks to accomplish. For example, [6], for natural gas pipelines, these tasks include:***measuring*** wall thickness;***detecting*** gas contamination in pipeline;***measuring velocity and flow*** of gas;***detecting presence of gas leaks***;***determining the variation in pipe cross-section***;***determining structural defects in pipes***, etc.

To be able to perform these functions WSN nodes are distributed along the transport pipeline as shown in Fig. 1. Geographical distribution of WSN nodes depends on the geometry of the area been monitored. In fig.2 are presented some variations of such distributions. It is obvious that the linear distribution (fig.2C) is suitable for pipeline infrastructure monitoring using WSN systems.

Usually, the sensor nodes of the network have a hardware architecture that includes: a sensor, a central processing unit (CPU), memory, a radio transceiver unit (RF) and a unit that provides electrical power. When a sensor node fails, its functions are covered by neighboring nodes. Main cause of failure of sensor nodes, the “dead” mode, consists is running out of power energy required for operation of the sensor node components.

It must be noted that there are times when some of the components of a sensor node can be disconnected from the power source when they are listed in the so-called "sleep" mode. For example, the time during which the components of the radio transceiver transmit data stored in RAM to the central dispatcher (CD) of the WSN, the sensor component can be put into "sleep" which totally disconnects it from the power supply. This shift into "sleep" mode is used in order to save energy from the battery which can not be recharged locally.

## Multi-hop communication technique

Since the covering radius, $R$, of the radio wave emitted by a node is small ($R$ <30m), a node can not communicate directly with the CD that are tens or hundreds of miles away. Therefore, we use the technique of multi-hop communications radio (one hop corresponds to a section of pipe between two neighboring nodes of the WSN). Multi-hop technique assumes that a node can only communicate with any of the nearest neighboring nodes. For example in figure 3 is considered a WSN composed of only three nodes whose locations are specified by coordinates ($x_i$, $y_i$, $i$ = 1, 2, 3).

From fig. 3 we can see that the node 1 can not communicate directly with node 2. The only possibility of communication between these two nodes involves using node 3 as a radio relay, applying hop-hop technique.

In fig. 4 are presented two cases (case A: $2d<R<3d$ and case B: $2d<R<3d$) of the linear distribution of the sensors used in pipeline infrastructure monitoring system using WSN in which the radius $R$ of the nodes is different.

From the figure it can be seen that the number of nodes that can communicate directly with each other depends on the ratio $R/d$. In A we have $1<R/d<2$, in which case a node can only communicate with two other neighboring nodes (neighbor from left and right). In case B we have, $2<R/d<3$, where one node can communicate with four neighboring nodes (two from the left and two from the right). In case A from fig. 4 the multi-hop technique uses the first neighbor as a radio relay station which can transmit the received signal to the nearest next node and so on to the relay which is in direct contact with the WSN CD. From this point of view the linear version from fig. 2C shows a poor reliability.

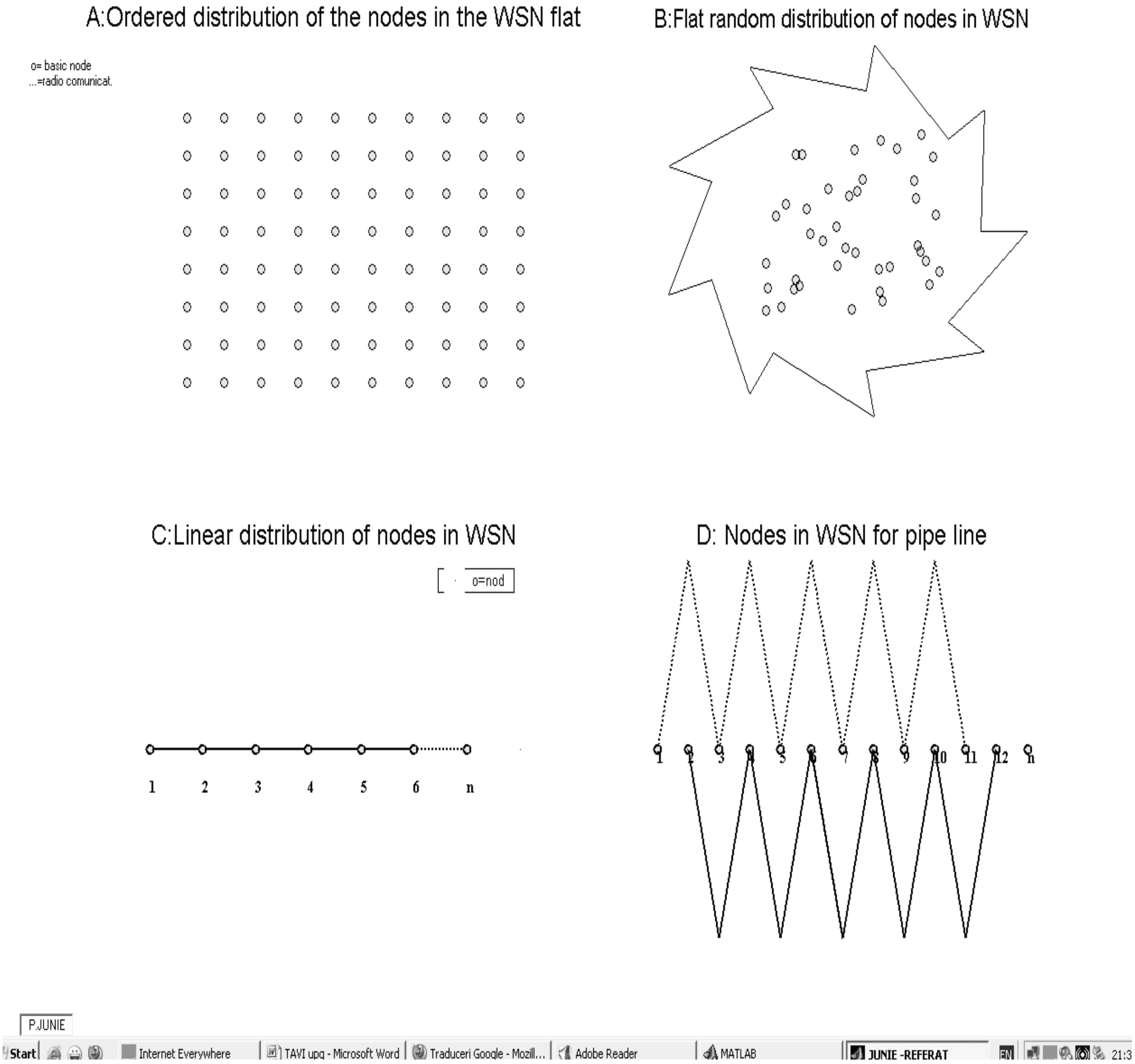


**Fig.2.** Geographic distribution of nodes in the WSN

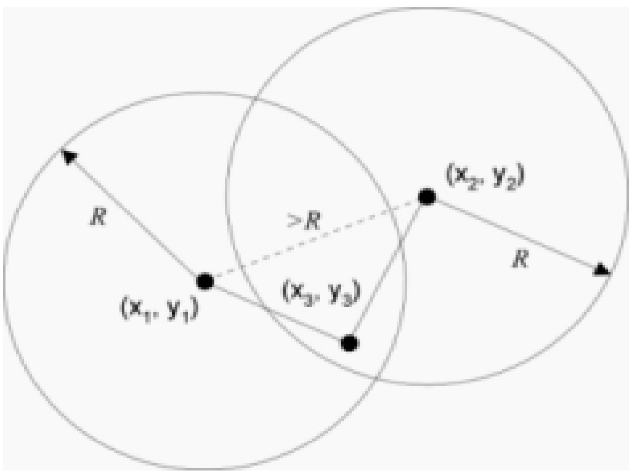


**Fig.3.** The communication between the node $i$=1 and node $i$ = 2 cannot be done directly because the distance between nodes $d_{12}> R$, so node $i$ = 3 is used as transit hub: hop-hop.

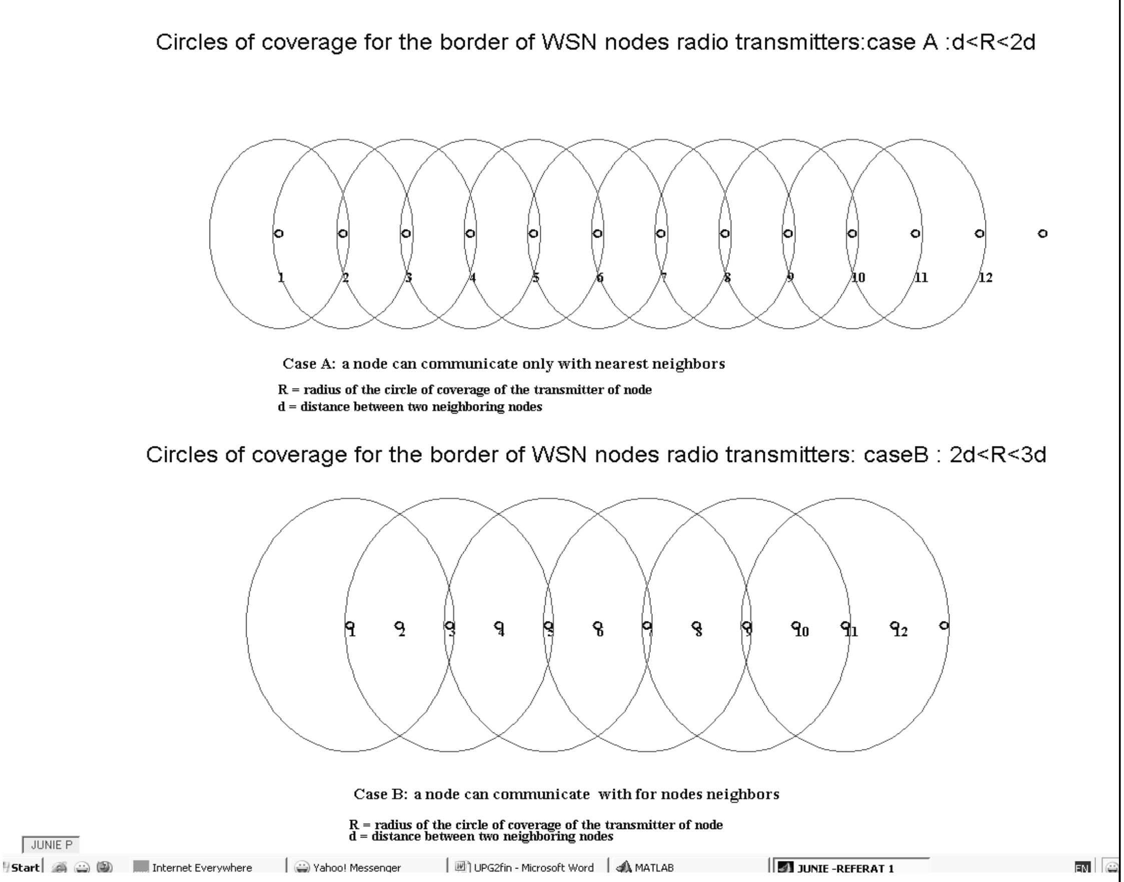


**Fig.4.** A) $2d<R<3d$ ; B) $2d<R<3d$

It is enough to fail one of the neighbours emiting node and the chain of radio relays will be broke; it remains a small number of nodes to communicate with the CD of WSN.A solution for increasing the reliability of WSN is as in fig 2D in which the communication protocol ensure 2 distinct communication paths with CD-WSN.Every node of WSN has a unique identificator (ID), an address which can be ordinated numbers.For one of the two paths which communicate with CD sensors node with odd number which communicate with CD and on the other the even numbers.In this case if a path is broken it remains the other way whattransmit to CD the informations in the vicinity of failed nodes.Through interpolation we can estimate the informations regarding to failed area nodes.

## Hierarhical architecture of a pipeline infrastructure monitoring system using WSN

From what we presented until now it is obvious that a pipeline infrastructure monitoring system using WSN is suitable to nodes hierarchy on levels:

- LEVEL 0 : node-sensor (NS)
- LEVEL 1 : node- Local Dispatcher(LD) collector date
- LEVEL 2 : node-Zone Dispatcher(ZD)
- LEVEL 3 : node-Central Dispatcher(CD)

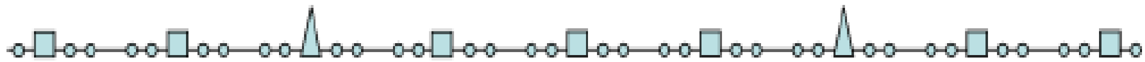

**Fig. 5.** A variant of in line distribution along pipeline of the hierarchical functioning nodes **[7]**

Distribution variant of the hierarchical functioning nodes presented in fig 5 is inspired from the structural dispatcher for the monitoring and control of the national energy system which has the same funtional structure: national dispatcher->regional dispatcher->local dispatcher->electric plants.

The hierarchical model of a WSN in fig 5 is a graph of tree type; the root is a ***CD*** and the leaves are NS.The branches are determined by the ***ZD*** and ***LD*** (fig6).

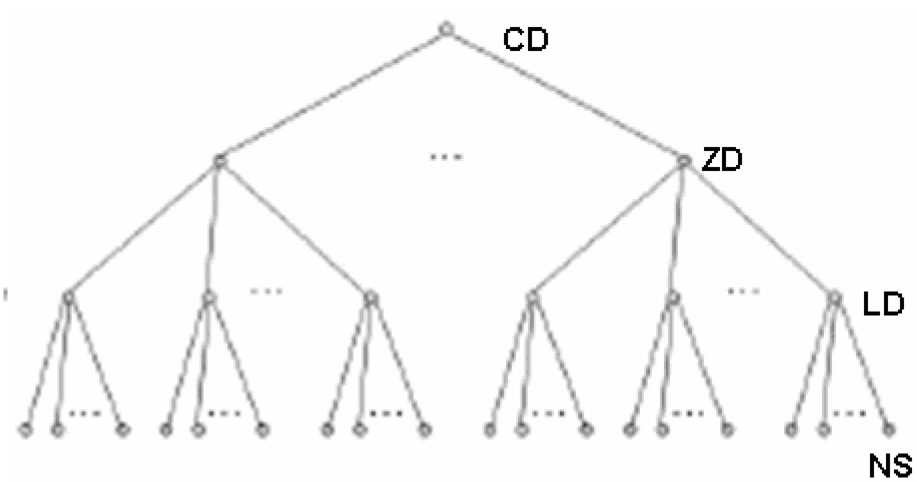


**Fig. 6.** Tree model of functional hierarchy nodes in pipeline infrastructure monitoring system using WSN

## Matrix Representation of Topology and Automatic Built of WSN Graph

Formally, a sensor network is represented by a scheme graph G($V$, $E$) where $V$ is the set of graphs nodes which represents the sensors nodes of WSN and the set of arrows E is represented by the radio conexions between the nodes in a network.We will consider a static network of wireless sensors represented by an unoriented graph G($V$, $E$).Every node $v \in V$ represents a radio transmitter of one sensor with a unique code (number) identificator (ID). In every moment a sensor can transmit or receive information from a single wireless channel.

The bandwith for every wireless chanel is $W$ and is split in 2 slots of time of $\Delta$ length.

Every node $v \in V$ have a circular transmission area of unit range and a group of neighbor nodes in the vicinity of v noted $N(v)$. This set of neighbourhood nodes are in the transmission range.So it exists a wireless bidirectional link between every node $v$ and every node $u \in N(v) - \{v\}$.These links are represented by arrows $(u,v) \in E$ .An example for this graph is presented in fig3.In the next lines we will use this simple network for illustrating the properties of the proposed algorithm for determinig in the presented model the shortest path between nodes $u$, $v$, in the sense of minimum distance noted $d(u, v)$ and which is the path where exists the minimum number of hops [8].

A WSN is composed by a number of sensors deployed on a geographic area. Every sensor has a wireless communication capacity and a certain level of intelligence of processingv of the signals and data.So I showed previously a WSN is represented formally by a network schematic graph.As an example the topologic model of the 2 SN from fig. 2 is a 3 node-sesor graph represented in fig. 5.

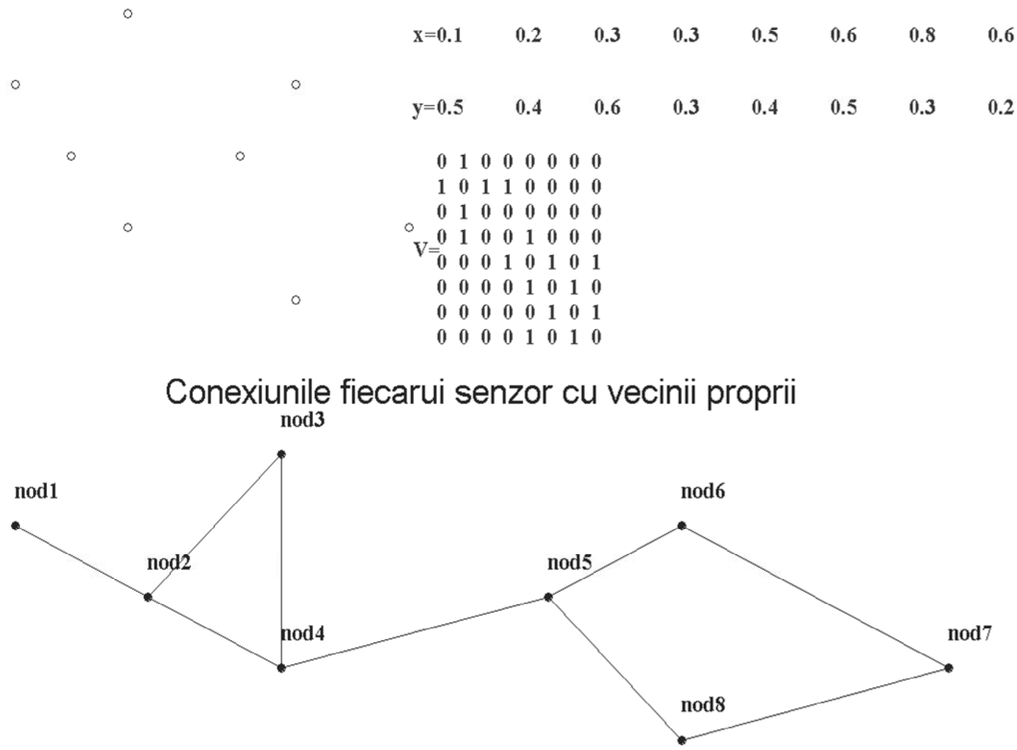


**Fig. 7.** Locations (x,y) and the characteristic vectors for WSN and the automatic built graph by the interactive system for automatic generation of some analytical-graphs models with Matlab command *gplot(xy,V,'k-).*

Every node-sensor of NS is characterized by its coordinates (*x*,*y*) of positioning of nodes-sensors in the plan through are represented the 3 points which represents the locations of the 3 sensors. A WSN is composed by a number of sensors deployed in a geographic area.The topologic model of WSN must reflect also the conexions between NS and also the coordinates (*x*,*y*) of the position in the 2D plan of every node of WSN. For the 2 categories of data we adopted representation with vectors of equal length with number of nodes from the graph what models the WSN. Taking into account that the Matlab language used by us for WSN simulation, operates in principal with matrix and vectors of data we proposed for defining the conexions by radio waves between nodes the association of a binary vector to every node of the network[5]. We noted it characteristic vector ***Vi*** of node *i* from WSN. In the case of WSN with *N* nodes-sensors, the characteristic vector has *N* length so it has an elements for every nod of the WSN.In the case of an detached node from the network all the *N* elements of the characteristic vector which represent this node are null. This emphasize the fact that this node does not has any node in his vicinity which to be conected.

In the case of a great number of nodes $N>15$ the representation become awkward because the length of characteristic vectors. In this cases we propose the split of the graph of WSN into clusters of moderate dimensions and an automatic generation of every separated graph. After that the total graph will be obtained uniting all the clusters graph. In fig. 9 there are presented the dialog boxes by introducing the coordinates locations of nodes-sensors of NS and of characteristics vectors of the nodes on the base which is built automaticly the WSN graph with Matlab command gplot.

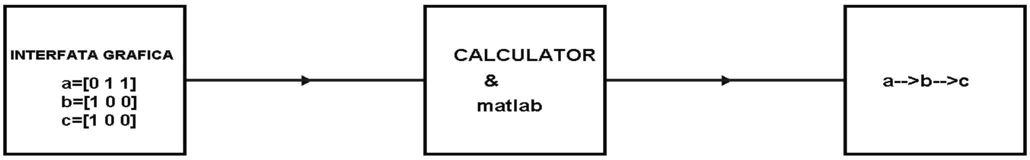


**Fig 8.** Schematic block of an interactive system for an automatic built of a WSN graph

For the locations of nodes-sensors are indicated the coordinates *x*, *y*.

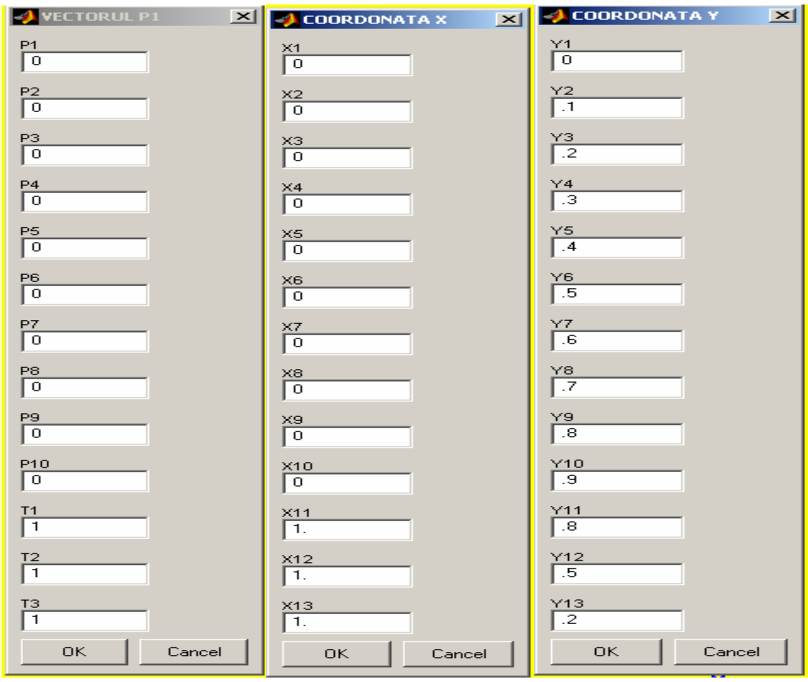


**Fig.9.** Dialog baxes destinated to data input x,y and characteristic vector nodes

These results are the base of the design of testing an interactiv system destinated to an automatic generation of a topologic –analytical model of NS. In fig. 8 is represented the block figure of this interactive system. The graphic interface of this system is realised using dialog box „inputdlg" available in Matlab. The graphic interface is used for data input which consist of characterisitic vectors *V* of the nodes and coordinates *x*, *y* of position of the sensor-nodes. As a response of data input from the user is listed on the monitor screen the graph and the data introduced like in fig. 7.

## Conclusions

In this paper there are presented some of own scientiffic research resulting in:

1) procedure of increasing the reliability of pipeline infrastructure monitoring system using WSN by realize 2 parallel paths of transmission multi-hop of information to odd and even nodes;

2) hierarchical structure of node functioning by the analogy with the hierarchical structure of monitoring the national energy system;
3) the inovation of matrix-vector representation of initial data for simulating in Matlab of WSN topology;
4) the conception and implementing of an interactive system for automatic generation by computer of the WSN topology.

We apreciate that the results obtaind can be developed much more in the future in the direction of optimisation of WSN topology in what regard to the perspectives for continue this research.

## References


1. * * * - Business Week: *21 technologies most important for the 21 st century*, 1999;
2. Borade, S., Zheng, L., Gallager, R. - Amplify-and-forward in wireless relay networks: Rate, diversity, and network size, *IEEE Trans. Inform. Theory*, vol. 53, pp. 3302–3318, Oct. 2007;
3. Gutierrez, J.A., Naeve, M., Callaway, E., Bourgeois, M., Mitter, V., Heile, B. - Ieee 802.115.4; a developing standard for low power, low cost wireless personal area networks. *IEEE Network*, 15(5), pp. 12–19, Sept/Oct 2001;
4. Jawhar, I., Wu, J. - Resource allocation in wireless networks using directional antennas. *The Fourth IEEE International Conference on Pervasive Computing and Communications (PerCom-06),* Pisa, Italy. Publisher: IEEE Computer Society, pp. 318–327, March 2006;
5. Tu, Y., Chen, H. - Design of oil pipeline leak detection andcommunication systems based on optical fiber technology. *Proc. SPIE*, 3737, pp. 584–592, August 1999;
6. Junie, P., Tertisco, M. - A Method to Identify Systems Based on Random Binary Events, *UPB Sci.Bull.*, Vol, XXX, No. 3, 2011;
7. Ozgur, A., L´evêque, O., Tse, D. N. C. - Hierarchical cooperation achieves optimal capacity scaling in ad hoc networks, *IEEE Trans. Inform. Theory*, vol. 53, pp. 3549–3572, Oct. 2007;
8. Ellul, I. - Pipeline leak detection. *Chem. Eng.*, pp. 40–45, June 1989;
9. Junie, P., Eremia, C. - Unele contributii privind modelarea topologica a retelelor de senzori fara fir (RSff), *Revista Română de Informatică şi Automatică*, Nr. 2, pp. 15-25, 2011.


# Monitorizarea infrastructurii conductelor utilizând rețele de senzori fără fir

## Rezumat


*Această lucrare prezintă unele rezultate ale cercetării ştiinţifice doctorale proprii privind monitorizarea conductelor de transport ţiţei şi gaze folosind reţele de senzori fără fir.*

*Reţelele de senzori fără fir (WSN în engleză) sunt o nouă arie de cercetare care cunoaşte o creştere rapidă datorită dezvoltării de noi tehnologii în domeniul senzorilor ieftini. Aceste dispozitive electronice au capabilităţi crescute în procesarea cu viteză mare a informaţiilor, memorie, comunicaţie, . Aceşti senzori au o vastă arie de aplicaţii incluzând monitorizarea mediului, militare, ecologice, agricole, controlul inventarului, robotică şi medicină. Lucrarea discută problemele şi provocările în utilizarea acestei noi şi provocante tehnologii în protecţia şi monitorizarea infrastructurii conductelor de transport petrol, gaz natural, apă, şi alte resurse importante.*

*Lucrarea prezintă un model arhitectural şi topologic care poate fi utilizat să ofere funcţii de control şi monitorizare. Modelul include o introducere asupra protocoalelor de rutare şi reţea care pot fi utilizate pentru a oferi comunicaţia necesară. În adiţional lucrarea oferă discuţii şi recomandări asupra fiabilităţii reţelei şi a utilizării diferitelor tehnologii de reţele wireless.*