Spatial and Energy Distributed Routing in Wireless Sensor Network

Jan Nikodem, Maciej Nikodem, Marek Woda, Ryszard Klempous

Department of Electronics, Wroclaw University of Technology

Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland

{jan.nikodem, maciej.nikodem, marek.woda, ryszard.klempous}@pwr.wroc.pl

***Abstract*— This paper strives for reflection on relational approach and its practical applications to distributed routing in Wireless Sensors Networks (WSNs). Considering the routing issue in WSN we looked for a solution that allows to define the global strategy for a network without giving detailed, explicit orders as those can interfere with nodes activities and may not properly react to local phenomena. Consequently we propose novel routing approach that is based on relationships and relational approach.**

***Keywords*— wireless sensors network, spatial communication, energy distributed routing, relations in complex system**

I. Introduction

The main task of WSN is to collect information from the area in which sensors are deployed. In order to perform this task it is necessary to retransmit information towards the base station. Hence, the two main interesting aspects of the network activity are: efficient implementation of routing and efficient distribution of energy consumption which obviously results from the network activity.

WSN is a distributed system as nodes are spread spatially but also due to the fact that functionality is also distributed. Individual components (nodes) can perform different, independent tasks, however, they are capable of executing much simpler tasks comparing to the tasks network was created to achieve. The obvious questions are: how to manage efficiently such large set of elements? How to ensure the appropriate cooperation, resulting in a globally desired effect? Indeed, WSN is a system of large complexity and there is only one tool which allows to master intellectually this complexity – an abstraction. Therefore, we are looking for new solutions in this domain. We have obtained promising results by applying the new approach based on the set theory and relations defined on it. Such approach is really native for WSN as actually everything that happens in the network is based on collections (sets of nodes, sets of routing paths, sets of neighbours i.e. neighbourhoods) and relations between them ("is a member of network", "is a cluster head", "belongs to a routing path"). Traditionally, literature presents methods based on functions which results from simplicity of such approach and the fact that most authors do not strive for different solutions. Functional approach, which makes the issue simpler, is more transparent and allows to grasp a certain part of the WSN complexity. However, at the same time it narrows considerations and analysis to a case study of a relatively small set of specific situations. These limitations, unavoidable on functional abstraction level, may be omitted at a higher level of abstraction, i.e. sets and relations. Relational approach enables decomposition of a global task (the routing towards the base station) to a number of small, local ones that can be completed by a single node of the network based on cooperation within its neighbourhood. Another enticement of such an approach stems from the fact that it leaves space for nodes interactivity.

II. Existing Approaches and Motivations for a New Method

Routing issues in WSNs are one of the most often covered topics in the literature (e.g. [1]-[3],[5]). Proposed algorithms cyclically perform three main steps:

- determination of optimal (according to some criteria) routing paths for transmitting messages,
- calculation of the costs of routing activity so that nodes of the network do not burden their energy unequally,
- cyclic repetition of the procedure for routing paths determination, in order to adapt routing to the current situation in each node of network.

Briefly speaking, our study looked for a new method of routing, which would devoid of this negative characteristics of previously proposed routing algorithms. Results presented in literature deal with the optimality of WSN operation in terms of time, space and cost: e.g. shortest packet delivery, minimum length communication path or lowest energy for packet delivery. No matter what optimality is taken into account, determining the routing paths is always done with respect to global criterion that requires information about the entire WSN. Collecting such information is time consuming as network of practical interest are large and consists of many nodes. Since data is collected over a long period of time, therefore, it is difficult to indicate the point in time when routing strategy determined was (or will be) optimal. Moreover, evaluating exactly one solution usually does not give information about other, similar routing strategies, that may not appear to be optimal from the point of view of the algorithm but may be useful for the network operation. As the result these routing algorithms give a solution which is more approximate rather than accurate. Furthermore optimality of resulting solutions is questionable.

This becomes particularly evident in the case of algorithms that minimize energy consumption during the routing activity. Resulting routing paths are the most energy-efficient but their determination absorbs energy and the total energy balance is no longer so promising.

Proposed method allows to determine collections of efficient routing paths that can be used for sending information towards the BS. The aim is to ensure many alternative paths, so each node can make choice when determining the neighbour to which packet should be sent. Since such a decision is made locally and independently for each data packet thus it is possible to guarantee the uniform distribution of energy cost of operation, between all network nodes. Leaving the determination of optimal routing paths we tend to implement routing activity as Pareto improvement process i.e. for a given set of routing paths we propose a way of evaluating them that will result in Pareto frontier. Result will be a set (Pareto set) of routing paths that are Pareto efficient. To restrict our attention to the set of choices that are Pareto-efficient, we can make tradeoffs within this set, based on relations between nodes. In future work we plan to extend the set of choices using less stringent Kaldor-Hicks efficiency criteria.

Our proposition of ranking alternative actions is to use drainage surface that is a sum of different surfaces spread over the network area. These surfaces reflect the preference of information flow and the number of surfaces may vary depending on requirements. For the simple case two surfaces can be used. The first surface is determined only once at the beginning of network activity during self–organization process. The second surface is determined at the same time but it is being modified during the network lifespan.

III. Principles of New Method

Our method aims to cover variety of actions that can be taken by each node of the network during routing determination. This cannot be done with traditional functional approach and new abstraction is needed. Our propose is to use three elementary relations that are presented in subsequent sections.

A. Relational Description of WSN Activity

Our approach utilizes binary relations defined on the set of actions *Act* that contains communication activities that can be taken in WSN. These three relations: collision χ, subordination π and tolerance ϑ were first introduced and described by Jaron [6] and later by Nikodem et al. [7], [8]. They are essential to describe variety of dependencies between real life objects (and also nodes of WSN). If we only consider two actions: packet transmission and reception, then subordination relation

$$x_R \; \pi \; y_S \tag{1}$$

means, that node *x* receives the packet whenever node *y* sends it. Subordination is transitive, so from *x* being subordinated to *y*, and *z* subordinated to *x* follows that *z* is also subordinated to *y* :

$$x_R \; \pi \; y_S \;\; \wedge \;\; z_R \; \pi \; x_S \;\Rightarrow\; z_R \; \pi \; y_S . \tag{2}$$

Subordination is not symmetric (it is asymmetric) which means that subordination of *x* to *y* implies that there is no subordination of *y* to *x*:

$$x_R \; \pi \; y_S \;\Rightarrow\; \neg\left(y_R \; \pi \; x_S\right). \tag{3}$$

Tolerance relation:

$$x_R \; \vartheta \; y_S , \tag{4}$$

indicates that node *x* may receive packet sent to him from node *y*. Since node *y* decides to which node send the packet to, therefore, it is less likely that *y* sends data to nodes that are in tolerance relation with it – it is more likely that packets will be send to subordinated nodes. Tolerance, in contrast to subordination, is a symmetric relation, that is:

$$x_R \; \vartheta \; y_S \;\;\Rightarrow\; y_R \; \vartheta \; x_S . \tag{5}$$

It follows that when *x* is in tolerance with *y* then also *y* is in tolerance with *x*. Moreover, if *x* tolerates *y* and *y* is subordinated to *z* then also *x* is in tolerance relation to *z*:

$$x_R \; \vartheta \; y_S \;\; \wedge \;\; y_R \; \pi \; z_S \;\Rightarrow\; x_R \; \vartheta \; z_S . \tag{6}$$

It is a property of both relations that all nodes that are in subordination are also in tolerance relation. In other words subordination implies the tolerance.

Collision is the last elementary relation. It identifies nodes that will not exchange any packet with each other:

$$x_R \; \chi \; y_S . \tag{7}$$

Equation (7) means that node *x* will not receive any packet from *y*. Moreover, collision is symmetric so *y* will neither receive any message from *x*. Additionally if *x* is in collision to *y* and *z* is subordinated to *x* then *z* is also in collision with *y*:

$$x_R \; \chi \; y_S \;\; \wedge \;\; z_R \; \pi \; x_S \;\Rightarrow\; z_R \; \chi \; y_S . \tag{8}$$

Nodes that belong to collision relation cannot belong to tolerance at the same time. Therefore, nodes that may be in collision can be neither in tolerance nor in subordination relation. The later comes from the fact that nodes that are subordinated constitute subset of nodes that are in tolerance relation.

Using relational framework to model packet transmission in WSNs, a neighbourhood relation η is also used. This relation is defined both for a single node of the network and for a group of nodes. It determines the set of nodes that are neighbours of a particular node or any node from the set, respectively.

It is worth to point out that the neighbourhood relation is of the great significance since whole activity of every WSN node is determined by the state of the node and its neighbours. Nodes operating within neighbourhood and according to relations π, ϑ, χ allow to achieve goals defined globally for the network. Neighbourhood is used to perform local activities and to choose the best tactics that will be implemented in practice.

We assume that neighbouring relation is symmetric, i.e.

$$x \eta y \Rightarrow y \eta x , \tag{9}$$

which means that if x is in relation with y (i.e. x can communicate with y) then y is also in neighbouring relation with x.

Using this relation we can define set of neighbours for a particular node *x*:

$$N(x) = \{ y \mid y \in \text{Nodes} \ \wedge \ y \, \eta \, x \}, \tag{10}$$

and for a group of nodes *S*:

$$N(S) = \{ y \mid y \in \text{Nodes} \ \wedge (\exists_{x \in S} \mid y \, \eta \, x) \}. \tag{11}$$

Using a neighbourhood abstraction we can also try to decompose globally defined activities to locally performed identical task ascribed to each node of the network. In general casting all global dependencies from network area to the neighbourhood is a difficult task, since situation in various parts of the network might be, and usually is, quite different.

B. Spatial Communication via Relational Attempt

Based on relational approach, in the paper [9] we have described the method of modeling spatial communication activity in wireless sensor network. Focusing on χ , π , ϑ and neighbourhood relations instead of looking for routing paths towards the base station (BS) (Fig.1.a) we consider all possible retransmission nodes (Fig.1.b) within the neighbourhood.

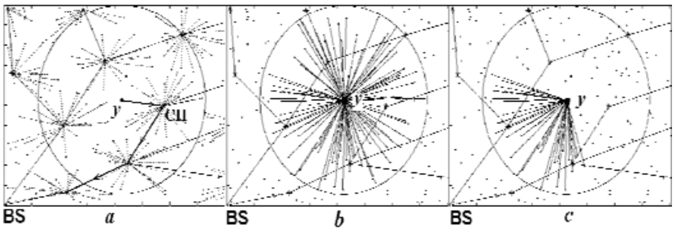

Fig. 1 Clusters (a) vs. Neighbourhoods (b) and subordinated (towards BS) directions (c) in node *y*

Our proposition of ranking of alternatives from a set of possible directions of retransmission (Fig.1.b) is based on usage a set of surfaces spread over the network area (these surfaces will be discussed later on). As a result of this process we obtain effective directions of retransmission (Fig.1.c).

Paper [9] presents, step by step, how to use relations χ , π , ϑ in order to model spatial communication. Subordination π is responsible for multi-hop path generation. A growing intensity quotient of π results in extension of different multi-hop paths in communication space. Relation π is responsible for a set of pontifixes (elements joining different paths). Tolerance ϑ is responsible for range of communication space. A bigger intensity quotient of ϑ widens communication space and extends possibility of parallel paths. However collision χ allows to form surface restrictions for the communication space.

Relational approach provides good tool enabling to profile communication space. Using this tool, it is possible to design required properties of communication space. It is possible to profile communication space to narrow or wider (ϑ) , to obstruct selected area (χ) and to favour other point as especially recommended freeways for information flow (π).

A local/global activity dilemma is a starting point of our consideration of modelling communication activity in WSN. We split all important aspects of communication activity into two classes. First class is composed of invariable aspects, while second class relates to aspects with local to global or local1 to local2 sensibility.

The network topology constitutes the first (invariable aspect) class. In contrast, node's energy states, cooperation and interference have been taking into account as the second (relative aspect) class.

Modelling data flow from a network area towards the base station is done similarly to the flow of rainwater. Packets produced by WSN nodes flow like raindrops streaming down in a direction determined by a slope of the modelled surface. During this process, drops merge with one another (data aggregation), carve terrain or build it like lava tears (energy consumption). A resulted flow depends on the local neighbourhood conditions and environmental stimulus (cooperation and interference).

We model natural network topology features using digital surface model (DSM). It is a component of a topographic map (bare drainage surface), which gives a basic reference frame that ensures packets are send towards the BS. In a real WSN nodes usually have no information about their Euclidean distance from the BS. Therefore, paper [9] proposes a measure of *dis*(*k*) (distance between BS and node *k*) based on the amount of hops (*h*) required to send packet from node *k* to the BS. We determine bare drainage surface (BDS) only once during network self-organization phase, so it is invariant during whole WSN lifespan. Superposition of BDS and relational surface constitutes effective communication space for each node (Fig.2).

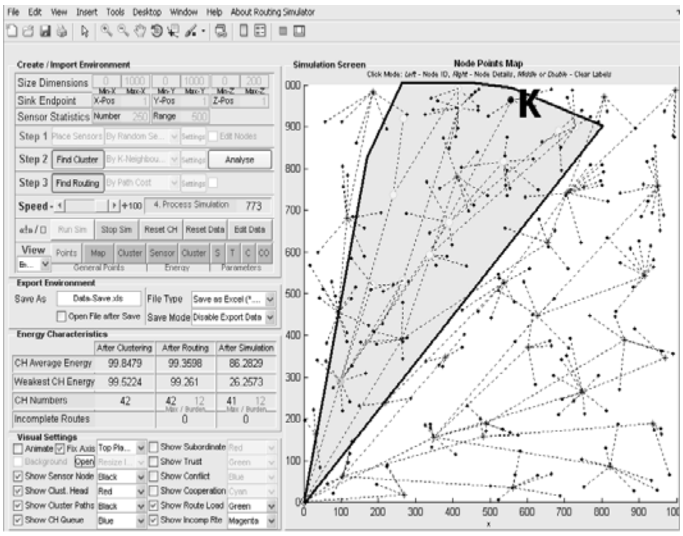

Fig. 2 Effective communication space for node K

C. Principles of Energy Distributed Routing

Based on the relational attempt, for each node in the network we can determine a set of efficient routing directions for sending a packet towards the BS (Fig.1.c). From many alternative nodes for packet retransmission, we can choose one, which guarantee (within the neighbourhood) the uniformity of the energetic burden to pay for sending a packet. The choice is based on residual energy remaining in each of neighbouring nodes that is represented as a surface stretched over the neighbourhood of each node.

In our routing implementation each node sends a packet to the neighbour node that belongs to the set of efficient routing. However, a sender chooses this neighbour node which has the largest residual energy. This simple rule ensures even distribution of energy consumption for each network node. Figure 3 presents how distributed routing allows to share a energy burden between collectively cooperating nodes. As a result, we obtain the ability to model the distribution of energy burden.

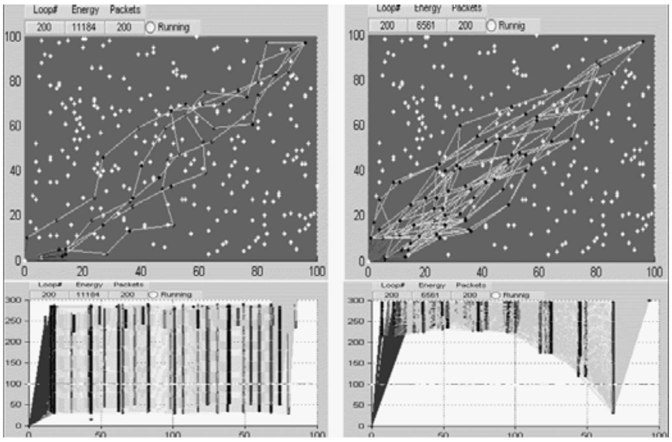

Fig. 3 Distribution of energy consumption in HEED algorithm (left) vs. novel approach (right)

Such mode of operation is adaptive and ensures protection of the nodes that have lower residual energy. In particular this refers to pontifixes, nodes strategically located on the crossings of many routing paths. Due to excessive load with retransmissions such nodes, in traditional algorithms, most often first deplete their batteries, thereby necessitating the calculation of a new routing path. Additionally, the proposed mechanism is a very effective tool to governance the cooperation between nodes during routing activity.

IV. Realization of Spatial and energy Distributed Routing

This paragraph describes how the novel, relation based routing in WSN was implemented. Software was run on Crossbow Technology Inc motes operating under control of Berkeley's TinyOS operating system.

A. Hardware and Software Environment

Hardware platform for evaluation of our proposal consisted selection of MICAz and Iris (Fig.4). motes developed by Crossbow Technology Inc. The motes used were MPR400CB equipped with CC1000 low-power RF transceiver operating at 900MHz and capable of measuring the battery voltage (used to power the mote). The USB-interfaced base station MIB520CB served two main purposes. First, it allows the user reprogramming any mote by plugging the mote directly into the base. Second, it operates as a part of the root node interface giving the PC a data conduit onto the radio based sensor network (all motes worked on the same frequency). Personal computer was connected to the BS and acted as operator's console with network address – ID=0x0000.

Hardware mentioned above worked under TinyOS operating system specifically designed for embedded networked systems. TinyOS has component based architecture, simply event based concurrency model and split-phase operations. All programs were written in NesC language which is extremely sensitive to hardware and software configurations.

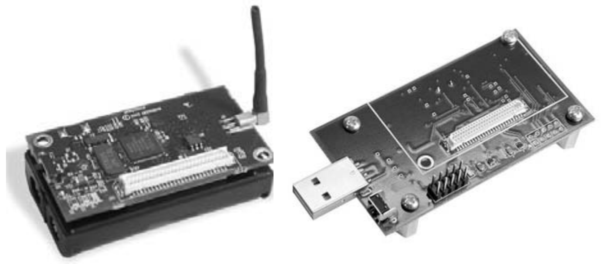

Fig. 4 Crossbow Techn. Inc. MICAz mote and MIB520CB base station

B. The structure of the packet's header.

Figure 5 outlines structure of packet's header. Only fields relevant to self–organisation on the network are presented:

DestNode ID	Message type	SrcNode ID	Sequence No.	Command type	..	

Fig. 5 The structure of packet's header

- DestNode ID, SrcNode ID are node addresses that may take any value from the range 0x0000–0xffff, where:
  - 0x0000 is address of operator's console (PC),
  - 0xffff is a broadcast address.
- Message type is a one byte field that determines packet type, precisely:
  - 0x00 – encodes message packet,
  - 0x01 – encodes command packet.
- SequenceNo is useful when broadcasting messages to avoid multiply retransmission of the same packet.
- Command type byte serves multipurpose. During self–organizing phase three values are valid:
  - 0x03 – prepare for routing command, cancel previous routing information,
  - 0x04 – start routing command,
  - 0x14 – acknowledgement of routing command.

C. Self-Organization Phase

Immediately after the power is turned on each node reads its address (ID) and the level of its battery voltage, turns on the radio and begins to sniff all the communication in its neighbourhood.

Self–organization phase starts when base station receives command 0x03 from the PC (ID=0x0000) with destination address set to DestNodeID=0xFFFF (broadcast command). This is a signal to prepare for the routing. Since this is ia broadcast command therefore it is broadcasted in the WSN. Similarly, any node of the WSN that receives such message stores the SequenceNo included in the packet and retransmits it further. Storing the last SequenceNo used ensures each node retransmits a broadcast command only once. Commands with the same or smaller value of SequenceNo are discarded. To avoid sudden spikes in demand on the transmission channel, each node retransmits command after a randomly determined time interval. The value of this delay is determined based on the difference between ID of the node and ID of node from which message was received. In this way, based on flooding technique the entire network learns to prepare for self-organization process.

During the process of flooding the network, nodes are sniffing the network activity out and create a matrix of their neighbours updating the number of neighbours and their address (ID).

The final step of network self–organization is initialized by personal computer again. From operator's console command 0x04 is send with destination address again set to 0xFFFF. This is a signal to construct spatial routing and it is broadcasted in the WSN from one node to another. SequenceNo parameter is used to ensure no node repeats the same broadcast message twice – nodes discard message with the same or lower SequenceNo. Again, to prevent jamming in the shared communication channel nodes retransmit command after a randomly determined time interval. Its value depends on the difference between node's ID and ID of nodes from which message was received.

Deja vu! Yes, moreover this is not very sophisticated algorithm. For command 0x04 each node executes nearly the same procedure as for command 0x03. The slight difference is explained on Fig.6 which presents an outline of packet's data field structure, where:

DescNode ID	HopDist	Battery voltage	Transmission power	...

Fig. 6 The structure of packet's data field

- DescNodeID is a node address (range 0x0000–0xffff):
  - in packets received, DescNodeID indicates the address of descender node, i.e. node downwards the base station,
  - while node sends packet, DescNodeID indicates its address to show potential ascenders the way towards the base station.
- HopDist (byte) serves only one purpose – to help receiver to determine bare drainage surface which slope allows packets streaming down (like raindrops) downwards the base station. Originally the base station sets this field to 0x00, later each node increases this value before retransmitting the packet.
- Battery voltage (two byte value) is useful for ranking of alternatives from the set of efficient directions of retransmission. Receiver uses this value to calculate energy remained in the preceding node (descender). Finally, receiver chooses node with the highest residual energy for future transmissions towards the BS. This approach guarantees (within the neighbourhood) that the energy consumption is uniform.
- Transmission power (two byte value) is useful for determining the relative distance between receiver and preceding node (descender). Comparing this value with the strength of received signal allows to calculate relative distance between sender and receiver.

During the self–organization phase each node that receives the 0x04 command in broadcast mode, determines:

- its distance from the base station, expressed in numbers of hops – this is equal to (HopDist+1),
- saves the following data about its predecessor
  - DescNodeID,
  - calculated residual energy,
  - calculated relative distance to it.

Next, node (which received the command 0x04) puts its ID, battery voltage and transmission power in DescNodeID, Battery and Transmission fields of the packet respectively, and actual value of HopDist. Afterwards, node sends that packet backwards (towards the base station) as a confirmation of finishing routing procedure. The confirmation packet has "Command type" field equal to 0x14 (command value + 0x10). Finally, node retransmits command 0x04 in broadcast mode with modified data fields.

D. Determining the Node's Neighbourhood

During the self–organization process each node receives packets with information about its neighbours. Based on this data node creates its neighbourhood matrix. The structure of this matrix is presented in table I. Policy of this data acquisition and of completing the fields of this table are given in the preceding chapter.

TABLE I

THE STRUCTURE OF NODE'S NEIGHBOURHOOD MATRIX

No. of neighbours =n	Neighbour ID(13)	Neighbour ID(22)	Neighbour ID(3)	...	Neighbour $ID(64)_n$
HopDist to BS	4	2	3		2
Battery voltage	2.891	3.124	3.116		2.916
Relative dist.	12.25	24.5	29.2		19.4

Row "*Relative dist.*" (distance) allows us optimizing the energetic burden to pay for retransmitting packets towards the base station.

Row "*Battery voltage*" is beneficial for ensuring even distribution of energy consumption in each network node. It allows to distribute communication costs of retransmission within all neighbourhood.

Row "*Hop distance to BS*" allows to create (based on relations χ, π, ϑ) a bare drainage surface discussed in the next chapter.

E. Building a Bare Drainage Surface within Neighbourhood

The node's neighbourhood matrix established during the self–organization process, contains all information necessary to implement the spatial and energy distributed routing in the network. There are many various feasible strategies for determining an effective communication space. Here, to outline the principles of the proposed method, we present only one and relatively simple strategy. For this purpose, we use relations χ, π, ϑ.

Consider an example presented in table I. The hop distance from considered node to the base station is equal 3. There are another nodes within its neighbourhood. Some of them are located closer (hop distance=2) while other are further (hop distance=4) from the base station. There are also nodes within neighbourhood which have equal hop distance. Bare drainage surface within node's neighbourhood is created using simple trivalent classifier (closer BS, at the same distance, further BS). For these three classes we assign appropriate relations: subordination, tolerance and collision. Primary set designating an effective communication space within these neighbourhood consists of two elements {ID(64), ID(22)} with possible extension to {{ID(64), ID(22)}+{ID(3)} if tolerance relation is taken into account. Table II presents nodes within neighbourhood ordered with respect to hop distance to the base station. This gives very simple, but effectively operating, bare drainage surface within neighbourhood.

TABLE II
THE NODE'S BARE DRAINAGE SURFACE MATRIX

No. of neighbours =n	Neighbour ID(64)	Neighbour ID(22)	Neighbour ID(3)	...	Neighbour ID(13)n
HopDist to BS	2	2	3		4
Battery voltage	2.916	3.124	3.116		2.891
Relative dist.	19.4	24.5	29.2		12.25
Relations	π	π	ϑ		χ

V. CONCLUSIONS

Implementing our proposal in NesC language and evaluating it with MicaZ motes allowed to verify WSN activity related to packet retransmission. Implemented algorithm was based on relations and set theory. Relational framework allows determining a global strategy for a network operation without giving detailed explicit orders that can interfere with nodes local activities.

We can determine, using relations, the recommended global routing areas (spatial routing), giving the nodes responsible for retransmissions possibility to explicitly choose a next path. The decision, which retransmitter to select, is taken completely locally and takes into account current situation in the neighbourhood. However, it is coordinated globally and thus fits into the operation strategies of the entire network.

In the created program relations were involved to create a drainage surface that determines direction of all routing paths and ensures that they convergence towards the base station. The drainage surface represents a natural network topology features helpful for routing and communication activity. The pivotal role and main goal of drainage function are – simplification of the next hop selection while routing the packet as well as to guarantee that chosen direction of data-flow is always correct (i.e. BS-oriented).

Relational approach was used to attain distributed routing. Three relations were defined: subordination, tolerance, and collision with properties that guarantee proper order within neighbourhood of each WSN node. Relational approach allows enforcing the required global strategy scenario that is prepared for the whole network by sending triplet of intensity quotients (subordination, tolerance, and collision). By a modification of these intensity quotients value, the drainage surface is being upheaval (communication is being blocked in that region) or lowered (communication activity is being intensified).

VI. ACKNOWLEDGMENT

This work was partially supported by E.U. Regional Development Fund and by Polish Government within the framework of the Operational Programme – Innovative Economy 2007-2013. The contract for refinancing No. POIG.01.03.01-02-002/08-00, Detectors and sensors for measuring factors hazardous to environment – modelling and monitoring of threats. ALA MA KOTA THE NODE'S BARE DRAINAGE SURFACE MATRIX

VII. REFERENCES

[1] D. Braginsky and D. Estrin, "*Rumor routing algorithm for sensor networks*", in Proc. of the 1-st Workshop on Sensor Networks and Applications, Atlanta, GA, pp.22–31, 2002.

[2] O. Fang, J. Gao, V.L. de Silva Guibas and L. Zhang., "*GLIDER: gradient landmark-based distributed routing for sensor networks*", in Proc. INFOCOM'05, vol.1, pp. 339–350, 2005

[3] A. Manjeshwar and D.P. Agrawal, "TEEN: a routing protocol for enhanced efficiency in wireless sensor networks", Proc. IPDPS'01, IEEE Computer Society, vol.3, pp. 2009–2015, 2001

[4] J. Nikodem, "*Designing communication space in wireless sensors network based on relational attempt*", ser. Lecture Notes in Computer Science, Berlin, Germany: Springer, vol.5717, pp.83–90, 2009

[5] O. Younis and S. Fahmy, "*HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks*", IEEE Transactions on Mobile Computing, vol.3, no.4, pp.366-379, October 2004

[6] J Jaroń, "*Systemic prolegomena to theoretical cybernetics*", ser. Scient. Papers of Inst. of Techn. Cybernetics, Wroclaw, Poland: Wroclaw Univ. of Techn., vol.45, 1978

[7] J. Nikodem, "Autonomy and cooperation as factors of dependability in wireless sensor network", in Proc. DepCoS – RELCOMEX 2008, pp.406–413

[8] J. Nikodem, R. Klempous and Z. Chaczko, "Modelling of immune functions in a wireless sensors network", in Proc. EMSS 2008

[9] J. Nikodem, R. Klempous, M. Nikodem, M. Woda and Z. Chaczko, "*Modeling a spatial communication activity in wireless sensors network*", in Proc. MAS 2009, pp.50-55