Intelligent Role-Based Routing for Dense Wireless Sensor Networks


*Albacete Research Institute of Informatics, University of Castilla-La Mancha 02071 Albacete, Spain
** University of Duisburg Essen Bismarckstr. 90 Building BC 47057 Duisburg Germany

Abstract—The task of routing data from a source to the sink is a critical issue in ad hoc and wireless sensor networks. In this paper, the use of fuzzy logic to perform role assignment during route establishment and maintenance is proposed. An intelligent role-based approach is presented and compared with similar existing routing protocols. Experiments show promising results for our proposal and its suitability for operating with dense networks, obtaining quick path creation and energy efficiency.

I. INTRODUCTION

Wireless Sensor Networks (WSNs), as well as other wireless personal area networks, have stirred up the world of wireless communications since they present new challenges in terms of energy efficiency and communications performance.

Sensor nodes are resource constrained in terms of energy, processing, storage and efficiency. This kind of networks also has to deal with problems such as mobility and reliability. All these problems make necessary some kind of network organization to create and maintain data paths and to ensure reliable and efficient communications among network nodes.

Routing data in a network, composed in many cases of a high number of low-resourced nodes, is a difficult task since the algorithms and protocols have to save as much energy as possible and offer good performance.

These protocols take into account important node features such as the remaining battery, number of hops to the sink, signal strength and so on. Not considering this information leads to problems in the network such as interrupted paths, data loss or isolated nodes, among others. These problems are directly related to latency and throughput values. Routing approaches provide network load balance to extend network lifetime, efficiency improvements, and data loss reduction. Network monitoring is also necessary to control topology changes and the addition or elimination of nodes in the network. The network lifetime will finish when the working routing protocol can no longer support the whole WSN.

In this paper, NORIA (Network rOle-based Routing Intelligent Algorithm), a novel routing algorithm for wireless sensor networks which combines different effective techniques is presented. These techniques are role assignment to distribute tasks over the network nodes and fuzzy logic for making decisions.

Role assignment means that nodes with greater resources will forward data flowing from more distant nodes up to the base station. The comparison of node conditions is performed by a fuzzy logic system, which speeds up route creation and makes it more reliable and efficient.

Our proposal is compared with two well-known routing approaches, a simple tree-routing algorithm and a Connected Dominating Set (CDS)-based routing algorithm. CDS-based routing has been widely used to perform routing over wireless ad hoc and sensor networks and will serve as a basis for checking the performance of our proposal. On the other hand, simple tree routing proceeds similarly to our proposal, allowing a fair comparison. The experiments show the efficiency of NORIA and its suitability for working with dense networks in an effective and reliable manner.

The rest of the paper is organized as follows: Section II details related work, Section III presents NORIA, our routing proposal. In Section IV, network problem resolution is explained. Experiments, tests and comparisons are detailed in Section V, and finally, Section VI gives some conclusions and lines for future work.

II. RELATED WORK

Sensor nodes are small and energy-constrained devices with limited computational capabilities and memory resources. Because of that, the development of a new generation of algorithms with new characteristics (such as self-organization, adaptation to dynamics, and generally a higher degree of distribution) is essential to fulfill the new requirements of sensor networks.

In [5] routing techniques for WSN are reviewed. This survey serves as a basis for future self-organization algorithms which will improve network efficiency. A general definition and classification of self-organization techniques in ad-hoc and sensor networks can be found in [6]. In [7], virtual structures such as backbone and cluster are proposed, but the necessity of wired nodes makes it not appropriate for wireless sensor networks. Previously, some general design paradigms for self-organized networking were proposed in [8] and [9]. These paradigms propose a new network organization model by introducing a new concept: the role.

Role assignment is a network organization technique which allows nodes or groups of nodes to have different functionality in order to improve network performance. Role assignment can be performed in several ways: rule-based paradigm [10, 11], application-based approach [12] or nodes-placement-based approach [13]. This work extends the rule-based paradigm in order to make decisions in the network.
consists in giving different functionality to each node or both local and neighboring data to make decisions. In the method for distributing tasks in a network. This technique an efficient manner of using nodes which are in a better functionality to nodes or groups of nodes in the network is role assignment because giving different techniques use for wireless ad hoc and sensor networks [14, 15]. In this work, CDS technique is going to be considered as a theoretical basis to compare our proposals. For that, we have implemented the routing approach appearing in [16], and its performance is going to be compared with our proposal. The operation of this protocol will be detailed in section V.

Our approach, NORIA, follows a fuzzy-rule-based paradigm. The nodes store and evaluate a set of fuzzy rules, taking into account both internal and neighborhood parameters. Role assignment and parent decision are performed according to the output of the inference engine, providing global energy saving and balancing data to nodes with a better state.

The idea of using artificial intelligence techniques to support the decision-making process in order to get more efficient algorithms is widely used in the recent bibliography. Nowadays, there are several algorithms that apply these techniques to ad-hoc network organization algorithms (e.g., approaches based on fuzzy-logic [17] machine learning [18], neural networks [19], genetic algorithms or ant colonies [20] can be found). Artificial intelligence techniques reinforce the efficiency and performance of self-organization algorithms, by combining data from nodes and their interactions in order to make decisions to improve global network performance. Decisions related to information transmission from source to sink are one of the most important aspects in sensor networks. Our approach tries to show how artificial intelligence techniques, specifically fuzzy logic, can support these decision-making processes to improve efficiency while extending the overall network lifetime.

III. ROUTING PROPOSAL

In this paper, we propose the use of a distributed routing algorithm that assigns roles to the network nodes, and creates energy-efficient routes to the sink. Distributed role assignment is implemented and nodes base their decisions on a fuzzy logic engine. This process is complemented with mechanisms to maintain paths and manage the addition and failure of nodes in the network.

A. Role Assignment and Fuzzy Logic

Our proposal uses role assignment, a well-known method for distributing tasks in a network. This technique consists in giving different functionality to each node or group of nodes in the network in order to globally improve the network's performance. These techniques use both local and neighboring data to make decisions. In the literature there exist several proposals based on role assignment which have been commented on Section II. Role assignment has been chosen because giving different functionality to nodes or groups of nodes in the network is an efficient manner of using nodes which are in a better state (lifetime, number of hops to the sink) to forward data in the network, preventing the batteries of forwarding nodes from running out, and thus avoiding data loss.

Since wireless sensor networks need simple and fast methods to make decisions, fuzzy logic appears as an appropriate approach due to its ability to calculate results fast and precisely. Moreover, the user-friendly nature of defining node conditions provided by this approach and the need for low processing resources makes this technique a suitable method for making decisions in wireless sensor networks.

Fuzzy logic is a decision system approach which works similarly to human control logic. It provides a simple method for reaching a conclusion from imprecise, vague, or ambiguous input information. The execution of a fuzzy-logic system requires less computational power than conventional mathematical computational methods such as addition, subtraction, multiplication and division. Furthermore, only a few data samples are required in order to extract the final accurate result. Besides, fuzzy logic is a handy technique since it uses human language to describe inputs and outputs [1].

One of the frequently-used fuzzy-logic inference methods is Mamdani [2], which consists of four phases: fuzzification, rule evaluation, combination or aggregation of rules, and defuzzification (see Fig. 1).

The input of a Mamdani fuzzy-logic system is usually a crisp value. To allow this value to be processed by the system, it has to be converted to natural language, that is, it has to be fuzzified. In this way, the fuzzifier method takes numeric values and turns them into fuzzy values which can be processed by the inference system. These fuzzy values represent the membership values of the input variables to the fuzzy sets.

Once values have been fuzzified, the inference system processes the fuzzy rules to get a fuzzy output. In the case of a fuzzy rule having more than one antecedent (conditional element), an AND (minimum) or OR (maximum) operator is used to estimate the output value of rule evaluation.

The third step in the Mamdani inference method is aggregation, where the rule outputs are combined to form a new fuzzy set.

Finally, in the defuzzification process, the new aggregated fuzzy set is converted into a number. Mamdani uses the centroid technique which tries to determine the point where a vertical line divides the combined set into two equal parts.

B. Fuzzy-Logic and Role-Assignment-based Routing

NORIA is an algorithm capable of creating and maintaining tree-based data paths in the network. The process starts at the base station (coordinator or sink) and it is propagated hop by hop until all network nodes are covered. Node conditions are evaluated using fuzzy logic and only those with better state (high remaining battery and low number of hops to the sink) act as data forwards.
The algorithm establishes minimum paths in terms of energy wasting, from every node to the coordinator, which gathers data coming from all the network nodes.

Roles are assigned in order to preserve low-resourced devices. Besides coordinator, the roles available are:

- **End device**: nodes that send sensed data to their parents.
- **Routers**: nodes that in addition to the former, also forward data coming from end devices and other routers.

To perform role assignment and parent (router) election, NORIA defines six kinds of message:

- **IPM (Information Propagation Message)**: includes local information such as: node ID, number of hops to the sink, remaining battery and role.
- **RDM (Role Decision Message)**: includes the same information as IPM, and it is interpreted by nodes as a trigger to initiate the self-organization process.
- **RRM (Router Request Message)**: this kind of message is used by nodes which do not have any router within their range (no node can forward their data), and requests an end device to become a router.
- **RCM (Role Changing Message)**: used by low-resourced router nodes to notify role changing (from router to end device), and requests their dependent end devices to look for another router.
- **ACK**: message to acknowledge addressed messages (no broadcast). It is used to control router presence and allows nodes to look for another parent in case of node failures.
- **DM (Data Message)**: sensed data is encapsulated in these messages.

The route creation followed by NORIA is summarized in Fig. 2. This process begins when the base station sends an RDM. Nodes receiving this message send an IPM and start a timer. During this time interval, nodes wait for information messages from neighboring nodes. Once the timer expires, the nodes use fuzzy logic to perform role decision and parent election, that is, selection of the best router from among reachable routers in lower level (lower number of hops to the coordinator). One-hop nodes will choose the coordinator as parent. If no router is found, a RRM is sent to the best (fuzzy-logic evaluated) end device neighbor. When nodes have selected role and parent, an RDM is sent in order to induce next hop neighbors to start the organization process. This RDM also informs the selected router about the new child.

Parent election and role assignment are based on the results of the evaluation of a fuzzy rules set. To perform the role assignment and parent selection process, nodes will compare the evaluation output for each neighbor node.

The input variables to be considered in the experiments are: number of hops to reach the base station and remaining node energy. These parameters are just a subset within the full set of parameters which can be included in the decision process (delivery probability, delay, signal strength... among others).

The output variable represents the suitability of the node for being a coordinator or for being selected as parent node. Figs. 3, 4, and 5 show fuzzy sets for input and output parameters.
The fuzzy sets used in this paper are an example of multiple possibilities and have been designed after several checks for the application and topologies used, in order to have a generic proposal which works in a wide range of WSN applications. It is important to note that fuzzy sets (input and output) can be customized depending on the application, requirements and circumstances of each particular WSN. For example, in a network that needs real-time data collection, the usage of the end-to-end delay as a decision parameter will be useful.

For that example, the fuzzy rule base includes rules such as the following: if the Number of Hops is Low and the Battery Level is High then the Node Suitability is Adequate. Here, since we have 4 fuzzy sets for Battery level input and 5 for Number of hops input, in total we have 20 rules, which are summarized in Table I.

### IV. SOLVING PROBLEMS IN THE NETWORK

During network operation, NORIA is able to control several situations related to node failures, new nodes coming to the network, and low-resourced routers. The algorithm manages these situations as follows:

- **Low-resourced router:** when a router realizes that its battery drops below a certain threshold, it sends a RCM. Then, children nodes will look for another router as seen in section III. Thus, nodes sending through the low-resourced router are re-organized and network connectivity is preserved.

- **Router failure:** if a node does not receive the ACK message from its router for at least two consecutive times, it will proceed as if it had received a RCM from its coordinator.

- **New node joining the network:** the new node listens to the channel. If some message from a router or from the coordinator is received, it is selected as parent. If no router or coordinator is heard during a pre-fixed period of time, the new node will send a RRM to the best end device heard and will select it as parent. The role of the new node will be end device (by default), being able to be changed into router if an RRM is received.

Furthermore, it is possible to re-organize the whole network or a part of it, if necessary or demanded by application requirements. We are currently working on this stage, so the implementation and experimentation of this part is left for future work.

### V. EXPERIMENTS

NORIA’s efficiency has been evaluated through its implementation in OMNET++ under the Castalia project [3]. This also enabled comparison with other protocols.

In this section, our proposal NORIA is compared with a routing scheme based on Connected Dominating Sets (CDS) [4], and with a simple tree-routing algorithm (STR).

A simple tree-routing algorithm has been chosen because it works similarly to NORIA, in the sense that STR builds a tree-based routing scheme but with the absence of roles, and taking into account different node and neighborhood conditions. STR operation can be summed up as follows: the base station announces its presence; the nodes that have received a base station announcement send their own announcement message and start a timer. When the timer expires, each node selects its parent node on the basis of the number of hops and link quality information. This procedure spreads hop by hop until all network nodes are reached.

CDS also uses roles to a certain extent by defining nodes inside and outside the set, but the procedure for calculating roles is different; CDS calculates roles before calculating routes, and NORIA performs role assignment at the same time as routes are created. The operation of CDS-based routing can be summed up as follows: first it computes a marking process in which the protocol calculates a CDS among all network nodes. After that, all nodes in the network are in the CDS, or are neighbors of at least one node in the set. This marking process selects nodes depending on their set of neighbors in order to keep all nodes in the network connected.

The routing process is divided into three steps:

- If the source is not a gateway host, it forwards the packets to a source gateway, which is one of the adjacent gateway hosts.

This source gateway acts as a new source to route the packets in the induced graph generated by the CDS.

![Number of packets during set-up phase](image-url)
Eventually, the packets reach a destination gateway, which is either the destination host itself or a gateway of the destination host. In the latter case, the destination gateway forwards the packets directly to the destination host.

### A. Setup and scenarios

The designed scenario has considered circular network areas with radius from $R$ (50m) to $10R$ (500m), maintaining constant node density (nodes per unit of area). Nodes are randomly located in these areas and the Base Station is located at the center. In the largest area ($10R$), 1959 nodes have been used. Table II shows the number of nodes for each experiment depending on network radius.

For each scenario and particular combination of parameters, we have run 100 simulations. The results express 95% confidence intervals in order to eliminate extreme values.

<table>
<thead>
<tr>
<th>Radio</th>
<th>Number of nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1R$ (50m)</td>
<td>21</td>
</tr>
<tr>
<td>$2R$ (100m)</td>
<td>81</td>
</tr>
<tr>
<td>$3R$ (150m)</td>
<td>177</td>
</tr>
<tr>
<td>$4R$ (200m)</td>
<td>317</td>
</tr>
<tr>
<td>$5R$ (250m)</td>
<td>489</td>
</tr>
<tr>
<td>$6R$ (300m)</td>
<td>709</td>
</tr>
<tr>
<td>$7R$ (350m)</td>
<td>973</td>
</tr>
<tr>
<td>$8R$ (400m)</td>
<td>1257</td>
</tr>
<tr>
<td>$9R$ (450m)</td>
<td>1597</td>
</tr>
<tr>
<td>$10R$ (500m)</td>
<td>1959</td>
</tr>
</tbody>
</table>

### B. Results

The first part of the simulation results shows the number of messages necessary to create the routes in the network using NORIA, CDS and STR. The number of messages used to create the routes is a good variable to evaluate the energy used in this process. The lower the number of messages sent, the lower the energy used. Fig. 6 shows the average number of packets sent by nodes during the simulations of the route creation phase as a function of the number of network nodes.

Note that NORIA and STR use the lowest number of packets to organize the network in the different experiments (see Fig. 6). These results prove the energy efficiency of our proposal, since the number of packets sent to organize the network is directly related to energy consumption. This metric is very important when working with networks composed of a high number of nodes (dense networks) and for applications that require proactive routing and cannot compute a route each time a node has to send data (reactive routing).

Our experiments have also shown that while NORIA and CDS are able to create routes for all network nodes, STR leaves an important section of the network unorganized. This section varies from 1 to 5% of the total amount of network nodes. This is caused by the decision approach implemented in STR, which fails to organize those nodes which cannot communicate with a signal power greater than 50%. In contrast, our experiments have shown that nodes whose signal is received below 50% power can still successfully send data to the sink.

Another important metric for the routing algorithms is the time taken to set up a fully-connected network. A low route establishment time is also propitious when solving problems in the networks, to create new routes, and to perform periodical set-ups, which is necessary for some applications. Fig. 7 shows the time taken by the different proposals to complete the route-creation phase.

The efficiency of our proposal has been proved since NORIA achieves the shortest time to organize the network, even taking half the time of other proposals such as CDS. These results make it suitable to be used in real-time networks, in which the user needs a fast response from the network.

The number of forwarder nodes in the network gives an idea of how many nodes will use more energy forwarding data from other nodes. Using data aggregation, the lower the number of forwarder nodes, the lower the global energy consumption. Fig. 8 shows the number of router nodes obtained in the experiments.

For this experiment, STR obtains the best value, followed by NORIA. But it is important to consider the problem of unorganized nodes left by STR. So we can conclude that NORIA obtains the best average results in the experiments, making it suitable to be implemented in real dense wireless sensor networks and to be used in a wide range of applications. Furthermore, role migration is performed (see Section IV) by using RCM messages to get load balancing avoiding node failure and data loss.

It is important to remark that no loops between nodes have occurred during simulations, that is, all created paths flow from any node in the network to the base station.
VI. CONCLUSIONS AND FUTURE WORK

The desire to improve the existing routing approaches for wireless sensor networks has led us to design and experiment with the routing algorithm presented in this paper. NORIA is a novel role-based routing algorithm that makes use of fuzzy logic to make decisions.

The algorithm has been described and evaluated. Simulation results show the correct operation of the algorithm and its suitability for use in a wide range of applications and scenarios. The performance of this proposal has been compared with two well-known routing methods and NORIA has proved its efficiency, by achieving better average results than the other proposals. The combination of fuzzy logic with role assignment to perform routing tasks has been proved to be a good association for working with dense WSNs.

Furthermore, the use of fuzzy logic makes node feature definition easier, and the accuracy and the low amount of resources needed to run the inference engine make this technique appropriate to be executed in the low-resourced nodes that make up wireless sensor networks.

The solution of network problems such as node failures, low-resourced routers and the addition of new nodes in the network is now being implemented and will be tested to evaluate the solutions proposed in Section IV. With this periodical monitoring, network operation will be extended and the efficiency and reliability of the network will be improved.

Many recent routing protocols assume that there are no collisions in the channel. They do not specify what MAC protocol is used or what mechanisms are employed for solving possible problems related to node scheduling. In our design [21], NORIA will really work in a collision-free channel since SA-MAC (a synchronous MAC protocol) solves this problem. In our architecture there are no suppositions, all protocols will work together to assure protocol) solves this problem. In our architecture there are no suppositions, all protocols will work together to assure

The algorithm has been described and evaluated. Simulation results show the correct operation of the algorithm and its suitability for use in a wide range of applications and scenarios. The performance of this proposal has been compared with two well-known routing methods and NORIA has proved its efficiency, by achieving better average results than the other proposals. The combination of fuzzy logic with role assignment to perform routing tasks has been proved to be a good association for working with dense WSNs.

Furthermore, the use of fuzzy logic makes node feature definition easier, and the accuracy and the low amount of resources needed to run the inference engine make this technique appropriate to be executed in the low-resourced nodes that make up wireless sensor networks.

The solution of network problems such as node failures, low-resourced routers and the addition of new nodes in the network is now being implemented and will be tested to evaluate the solutions proposed in Section IV. With this periodical monitoring, network operation will be extended and the efficiency and reliability of the network will be improved.

Many recent routing protocols assume that there are no collisions in the channel. They do not specify what MAC protocol is used or what mechanisms are employed for solving possible problems related to node scheduling. In our design [21], NORIA will really work in a collision-free channel since SA-MAC (a synchronous MAC protocol) solves this problem. In our architecture there are no suppositions, all protocols will work together to assure the best performance of the sensor network.

Our future work is now focused in the incorporation of other parameters to the decision system (end to end delay and delivery probability, for example) as well as the integration of the different components of the architecture and the experiments with NORIA in real wireless sensor networks.

ACKNOWLEDGMENTS

This work was supported by the Spanish MEC and MICINN, as well as European Commission FEDER funds, under Grants CSD2006-00046 and TIN2009-14475-C04 and the Regional Council of Science and Education of Castilla-La Mancha, PB108-0228-9935.

REFERENCES