Smart Wireless Design Scheme: Fuzzy-Logic Routing and TDMA MAC Protocol Integration

Antonio M. Ortiz
Institut Mines-Telecom,
Telecom SudParis
France
antonio.ortiz_torres@it-sudparis.eu

Fernando Royo
Playa de las Teresitas
Tenerife
Islas Canarias, Spain
froyo@dsi.uclm.es

Teresa Olivares
University of Castilla-La
Mancha
Spain
teresa@dsi.uclm.es

Noel Crespi
Institut Mines-Telecom,
Telecom SudParis
France
noel.crespi@mines-telecom.fr

Luis Orozco-Barbosa
University of Castilla-La
Mancha
Spain
lorozco@dsi.uclm.es

ABSTRACT

Integration of algorithms and protocols from different layers will make possible the deployment of large-scale wireless sensor networks. The growing number of nodes that comprises within these networks requires a correct organization and an efficient node synchronization to ensure data reliability. In this study, we focus on the integration of fuzzy-logic based routing with a TDMA MAC protocol. By considering the experimental results of them working separately, we have integrated them to work together, so forming a cross-layer framework. By using a fast configuration and efficient slot assignment from the MAC protocol, and the accuracy of the logical tree created by fuzzy logic based routing, nodes in the network are both organized and synchronized, while load balance is achieved to extend network lifetime and provide efficient communications.

Keywords

Integration, Wireless Sensor Networks Design, Fuzzy-logic, Routing, TDMA MAC.

1. INTRODUCTION

Wireless sensor networks (WSNs) comprise a large number of sensor devices that communicate with each other via wireless channels, with limitations of energy and computing capabilities. The efficient and robust realization of such large, highly-dynamic and complex networking environments is a challenging algorithmic and technological task [3].

Our research addresses a cross-layer-based approach, working with the components of an emerging general-purpose sensor networking infrastructure. Networking is important because it provides the glue that allows individual nodes to collaborate. Radio communication is the major consumer of energy in small sensor nodes. Thus, the optimization of networking protocols can greatly extend the lifetime of the sensor network as a whole [6].

This paper focuses on both the link and network layers. The former layer is approached by considering a media-access control (MAC) protocol, and topology control and a self-organization algorithm are discussed for the latter. The MAC layer manages the communication channel available for the node, and so must avoid collisions and errors in communication, while the network layer selects the communication paths by considering diverse metrics.

Organizing a network, composed in many cases of a high number of low-resourced nodes, is a difficult task since the algorithms and methods have to save as much energy as possible while offering good performance. Power saving has been the main driving force behind the development of several protocols that have recently been introduced. In this context, perhaps the highest energy savings are achieved by protocols whose communications are based on time division multiple access (TDMA) and synchronization. However, synchronous communications require the organization of the network nodes in an efficient structure such as a logical tree.

Our work integrates the SA-MAC protocol [13], a simple but effective collision resolution protocol as a means to set-up the slot allocations of TDMA protocols, with NORIA (Network Organization Rule-based Intelligent Algorithm) [9], a novel self-organization algorithm for wireless sensor networks. This paper shows SA-MAC and NORIA working together in a dense network. Results for MAC layer evaluation and network layer evaluation are shown, as well as for the integration of NORIA and SA-MAC, offering a cross layer solution to improve the efficiency of network communications.

The rest of this paper is organized as follows. Section 2 discusses some related work. Section 3 describes the fundamentals of the synchronous MAC protocol, SA-MAC. Section 4 briefly describes the fuzzy logic system used. In Sec. 5 the network self-organizing algorithm NORIA is described. Section 6 shows the integration of SA-MAC with NORIA, and analyses simulation results. Finally, section 7 concludes the paper.

2. RELATED WORK

TDMA MAC protocols avoid some important problems such us idle listening, collisions, overhearing and overhead due to control packets. In addition, when an efficient global synchronization mechanism is available, the topology is fairly stable and TDMA protocols are usually the best option for efficient data communications in WSN [8]. A few relevant MAC protocols that make use of TDMA channel sharing are worth mentioning in [13]. These protocols normally use a separate protocol or an add-on hardware for synchronization in indoor environments and an atomic clock receiver for outdoor operation. SA-MAC protocol solves this set-up phase successfully and performs a second phase of synchronization and data transmission.

It is also strongly recommended for a MAC protocol to be distributed and self-organized to support topological changes, since these features are essential to ensure the efficient scalability of a wireless sensor network [7]. In order to do this, we integrate SA-MAC with NORIA, which will create the communication paths (i.e., logical tree) in an optimal and intelligent manner, by considering the differences among nodes and selecting the most adequate.

In [1], different routing techniques for WSN are described. These techniques serve as a basis for future self-organization algorithms which are intended to make the network more efficient. As for classification of self-organization techniques in ad-hoc and sensor networks, a general definition is found in [5] and some general design paradigms for self-organized networking are proposed in [15].

After all, we have come up with the idea of using artificial intelligence techniques to help the decision-making process in order to get more efficient algorithms. Nowadays, a number of papers propose algorithms that try to use these techniques in ad-hoc network organization algorithms; machine learning [18] or neural networks [2] are some examples. Artificial intelligence techniques reinforce the efficiency and the 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 a source to the sink are one of the most important aspects in sensor networks. Our approach shows how artificial intelligence techniques, specifically fuzzy logic, can help these decision-making processes to improve efficiency and to extend network lifetime.

A relevant study combining fuzzy rules with networking can be found in [11], where the authors propose two asynchronous MAC protocols, they make a complicated schedule interval and design a rescheduling fuzzy logic system to monitor the influence of accumulative clock-drifts, the variance of traffic strength and service capability on communications. In the experiments, they increase the number of nodes within a cluster from 5 to 30, and exclude the factors coming from physical and network layers to simplify the analysis.

Another interesting approach is presented in [17], that introduces FuzzyMAC, a CSMA/CA-based MAC protocol that utilizes two separate fuzzy logic controllers to optimize both the MAC parameters and a sleeping schedule duty-cycle. The experiments only show results for 50 nodes and use a proprietary simulator.

Our approach presents the combination of a MAC and a routing protocol working together in a cross-layer framework with the aim or outperforming network efficiency.

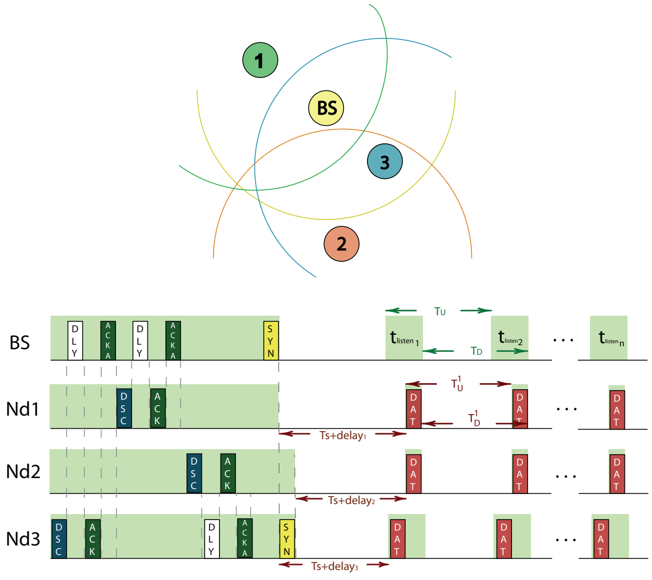


Figure 1: SA-MAC timing diagram.

3. SYNCHRONIZED MAC

Bearing in mind the need for developing an energy-efficient approach, we have undertaken the design of SA-MAC: a node synchronization engine. SA-MAC addresses two of the main issues in the area of protocol engineering for wireless sensor networks: power consumption and transmissions synchronization.

3.1 SA-MAC Protocol overview

In this section, we define the operation of a TDMA protocol for scheduling communication slots. Without loss of generality, we take as case study the set-up phase of SA-MAC, a TDMA protocol specifically designed for wireless sensor networks.

The main objective of the SA-MAC protocol is to synchronize the ON/OFF periods of senders and receivers. In the following, the protocol operation will be described by considering a network consisting of a sink node responsible for gathering all the data sensed by all the other nodes. Some of the other nodes may have, when required, to act as relays enabling the collected data forwarding towards the sink node (i.e., base station).

The operation of SA-MAC is divided into two phases: 1) the set-up phase and, 2) the synchronization and data transmission phase. In this paper we will briefly describe both of these. Other aspects of the protocol operation can be consulted in [14].

During the set-up phase of the SA-MAC protocol the network nodes exchange four types of packets, namely discovery packets (DSC), delay packets (DLY) and acknowledgement packets (ACK and ACK-ASOC). In the simplest scenario the set-up phase starts when the base station announces its presence as a parent node so that all other nodes can start trying to establish a father-and-child relation. Thus, all nodes that become aware of the presence of the base station start to broadcast discovery packets (DSC). Upon receiving a DSC packet, the base station sends a DLY packet to the corresponding node. The delay packet indicates the time slot that is assigned for transmissions from the sensor node to the base station. The node acknowledges the DLY packet with an acknowledgement packet, ACK, and this acknowledgement packet will be replied to another one from the parent node named ACKASOC. In this way, the sensor node finishes its association to the base station and then it may become a parent node for other nodes.

When the network has been created, the BS waits for a period of time, during which no new nodes are detected. The BS node will then transmit a SYN packet indicating the beginning of the data transmission phase. This process starts at the base station and a SYN packet is propagated among successive levels. Figure 1 shows a possible sequence of actions described for an scenario with a base station (BS) and nodes Nd1, Nd2 and Nd3.Let us assume that Nd1 and Nd3 are located within the coverage area of the BS and that Nd2 is located within the coverage area Nd3, but out of reach of the BS.

During the second phase, the nodes will turn ON and OFF, thus completing a duty cycle. Each node will send its data to the parent node scheduled during the set-up phase of the protocol. As already stated, all children transmissions will be scheduled within an ON epoch. This is to say, the parent node will wake up and each node will transmit within the slot allocated during the set-up phase. In this way, we limit the overhead due to the transient period every time the radio interface is turned on.

In order to keep the nodes properly synchronized, it is clear that each node has to transmit within the time slot reserved for it (see Fig. 2). Letting *n* denote the number of children nodes associated to a parent, the following condition has to be met for proper synchronization:

$$t_U^f < t_U^1 < t_D^1 < ... < t_U^{n-1} < t_D^{n-1} < t_U^n < t_D^n < t_D^f \qquad (1)$$

where t_U^f, t_D^f, t_U^i, t_D^i denote the upper-edge and lower-edge transitions of the radio interfaces of the parent node and those of the i^{th} child node, respectively.

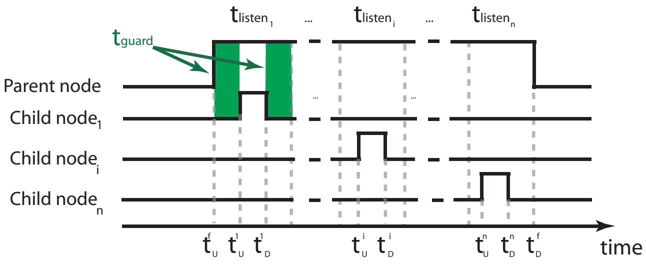


Figure 2: Time wise synchronization.

The proper operation of the SA-MAC protocol requires a child node to make use of the time slot assigned by its parent node, where t_{guard} is the maximum drift allowed to the node to keep the synchronization. Physical node properties, in particular the physical differences of their oscillators, will make it difficult to indefinitely index the transmission period, thus requiring periodical re-synchronization in order to avoid data loss. A complete analysis of the re-synchronization interval was carried out in [14]. In practice, the length of frame synchronization will strongly depend on the technology being used.

Table 1: Relevant simulation parameters.

CSMA/CA		SA-MAC	
Parameter	Value	Parameter	Value
macMinBE	3	$Radio_{datarate}$	250 kbps
aMaxBE	5	$Radio_{range}$	50 m
MaxCSMABackoffs	4	T_{packet}	1.164 ms
AckWaitDuration	3 ms	$Slot_t$	1.164 ms
aMaxFrameRetries	5	T_S	15 min
		$CPU_{clockdrif}$	40 ppm
		Tx_{power}	62 mW
		$Listen_{power}$	62 mW
		$Sleep_{power}$	1.4 mW
		Rx_{power}	62 mW
		t_{listen}	50 ms
		t_{guard}	25 ms

3.2 Performance evaluation

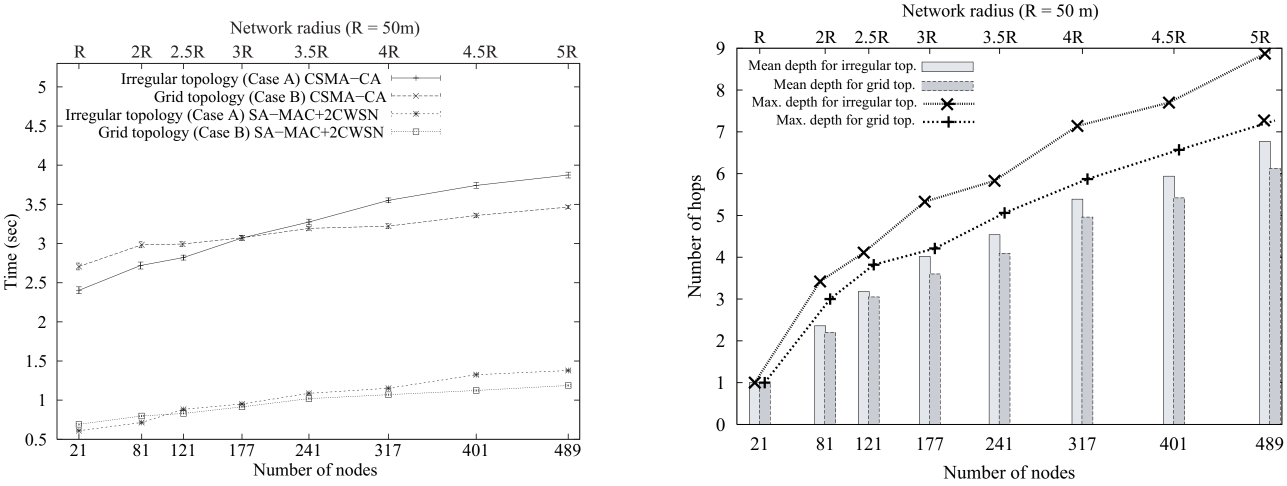
In this section we study the performance of SA-MAC in different scenarios. Our aim is to identify and assess the effect of relevant factors on the protocol performance. For performance evaluation we implemented SA-MAC using OMNET++ [16] and the Castalia pro-ject [4]. This simulator has been selected due to it is an open-source solution, which is continuously updated and it is used by many research institutions. We made use of the simulation model for the radio chip CC2420 as implemented in the Castalia project, also CSMA/CA model has been implemented to compare the time-efficiency achieved during the set-up phase. Table 1 lists the most important parameters used in our simulations.

In order to investigate the effect of node density and network nodes spatial distribution for the set-up phase algorithm, we set up the scenarios described below.

- Case A. Irregular topology and increasing area. Nodes are placed randomly around incremental circular areas with the base station located at the center. We considered areas with different radii from *R* to 5*R*, but we maintained a constant node density. In the largest area we used as many as 489 nodes.
- Case B. Grid topology and increasing area. In this case the nodes were placed randomly at the different intersections of a grid pattern. Although it is generally assumed that sensor nodes will most likely be deployed at random, we used this scenario in order to compare with Case A and determine the effect of having equidistant nodes on the association procedure. We used the same assumptions and parameter values as in Case A.

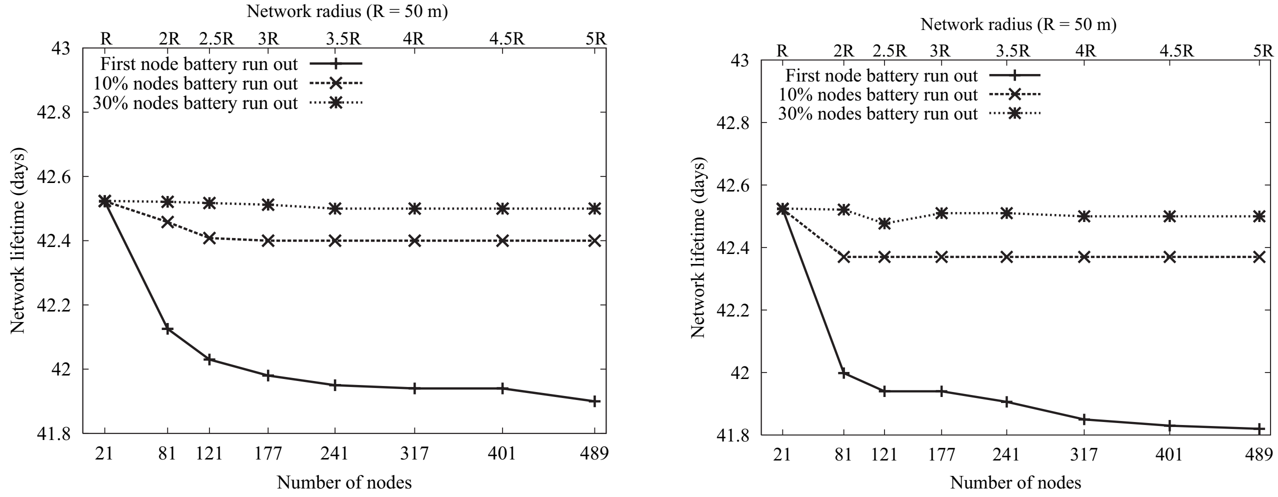
For each scenario and a particular combination of parameters we ran 1000 simulations in order to obtain 99% confidence intervals for the mean network creation time. This metric is defined as the time elapsed between the announcement from the base station regarding its presence, until the time when the last node association has finalized in order to configure the whole network. This parameter will show us the time required to complete the set-up phase.

Figure 3a shows the behaviour of the creation time as a function of the network size. When the network includes the nodes that are



(a) Network set-up times for Case A and B.

(b) Max./Average number of hops for Case A and B.



(c) Network lifetime Case A.

(d) Network lifetime Case B.

Figure 3: Performance obtained during set-up phase of SA-MAC and network lifetime obtained over time.

furthest away from the base station, the time required for network creation increases. Nevertheless, the growth rate is rather slow. If we compare the set-up resolution time obtained with CSMA/CA, we confirm that the resolution algorithm used in SA-MAC reduces it significantly.

We also collected statistics regarding the depth of the generated tree. Figure 3b confirms that, in the last ring for both topologies, the mean tree depth approaches the network radius (XR) used in each test. However, the simultaneous progress of various branches in the tree leads to the possible appearance of unnecessary hops, as the maximum number of hops for each one is shown.

This result shows that it is feasible to use SA-MAC in large networks because its set-up phase is able to quickly schedule the slot assignment.

The synchronization and data transmission phase shall be evaluated according to the network lifetime achieved over time, when the network is re-synchronized and new nodes appear or others disappear. According to Table 1 we can simulate the network workload until the first's battery wears out, or some percentage of batteries are wearing out. For this study, a monitoring application is loaded, which sends the data every 8 seconds and works with SA-MAC. The re-synchronization interval is studied for the worst case, and using the clock drift from Telosb datasheet [10], and the t_{guard} defined, we can calculate the maximum synchronization interval as:

$$drift = \frac{(time\_since\_last\_sync) * (freq\_error\_in\_ppm)}{10^6} \quad (2)$$

We obtain a value of 625 sec. for the drift time, for one node. If we consider that communication is carried out between two nodes, the worst case will be when the clock drift of the receiver and that of the sender go in opposite directions. Therefore, we chosen a value of 300 sec. as the re-synchronization interval, so covering the worst case. Figures 3c and 3d show the results for both cases. We can see how the size of the network directly affects the battery run-out of the first node and after that the gap between 10% and 30% remains stable.

4. FUZZY LOGIC

Fuzzy logic is a decision system approach which works similarly to human control logic. It provides a simple way to arrive at a definite conclusion based upon 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 [12].

All these features make fuzzy logic appropriate for the parent selection process in wireless sensor networks. Since this technique requires low computational capabilities, and it is able to get a high efficiency with a few data samples, we will use it in the parent selection process and also will take advantage of the combination of different input variables.

The next section overviews the NORIA routing protocol, detailing its operation mechanism as well as the fuzzy logic principles considered.

5. NETWORK SELF-ORGANIZATION

Self-organization is a key element in the operation of wireless sensor networks. Paths from any node in the network to the base station must be defined in order to get efficient network communications. With the use of fuzzy-logic, we expect to get successful results in terms of network organization time and number of hops from any node to the base station, always selecting the best parent in terms of energy and number of hops to the sink.

In this paper we propose NORIA (Network self-Organization Rule-based Intelligent Algorithm), a self-organization algorithm for WSNs which uses a decision process based on fuzzy-logic. This algorithm is the evolved form of NORA, a role-based self-organization algorithm.

5.1 Role-based approach

NORA (Network Organization Role-based Algorithm) [9] is a routing algorithm capable of self-organizing a network by creating a communication tree. The process starts at the base station and it is then propagated hop by hop until cover all the network nodes. Node conditions are evaluated and only those with better state (battery, number of hops to the sink) act as data forwarders (parent nodes).

The algorithm establishes minimum paths, in terms of energy consumptions, from every node to the base station, which gathers data coming from all the network nodes. Roles are assigned to network nodes in order to balance the network load. These roles are $leaf$: nodes that sense the environment and send data towards the base station, and $master$: nodes that as well as performing $leaf$ node tasks, also rely data from other nodes to the base station.

NORA defines four kinds of messages in order to organize the network and send collected data. These messages are: IPM (Information Propagation Message), which includes local information; RDM (Role Decision Message), which informs about selected role, MRM (Master Request Message), to request neighbor role changing, and DM (Data Message), which includes requested and/or forwarded data.

The algorithm consists of two stages: first, the algorithm organizes the network by creating the communication tree, which is routed at the base station, and by fixing as forwarder master nodes those with better conditions. The second stage is still under development, and performs periodical verification, which includes, if necessary, role migration in order to provide load balancing and to avoid node overloading. The organization procedure for each node is summarised in Fig. 4.

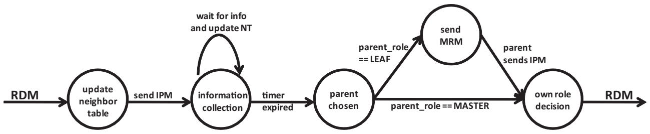


Figure 4: NORA organization phase transitions.

5.2 Fuzzy-logic network self-organization

In order to improve NORA's performance, we propose the incorporation of fuzzy logic to the decision process, which is where NORIA (Network self-Organization Rule-based Intelligent Algorithm) comes into play. Thus, parent election is now based on the results of the evaluation of a fuzzy rules set.

The necessity of having updated information about same-level neighbors (maintained by IPMs) to perform role election, with its consequent energy consumption, has led us to eliminate role assignment. With this new premise, nodes are free to select the best node to forward their data. It is at this point where fuzzy logic acts. Nodes will select as parent the node that gets the best value after fuzzy logic evaluation, making paths energy-efficient, with the consequent global energy saving of the overall network.

The input variables to be considered in this experiments are: the number of hops to reach the base station, and the residual energy level. This parameters are an example of the full set of parameters which can be also included in the decision process (e.g., delivery probability, delay, signal strength, etc.). The output variable represents the suitability of the node to be selected as parent node. Figure 5 shows fuzzy sets for the output parameter.

Nodes will compare the output of the evaluation for each neighbor node to perform the parent selection process. Note that fuzzy input and output sets can be customized depending on the application and on the circumstances of each particular WSN. For example, in a network which needs real time data, it will be interesting the use of the end to end delay as a decision parameter.

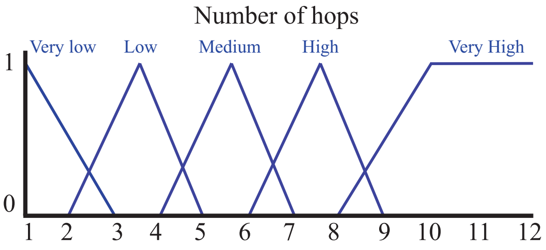


Figure 5: Number of hops fuzzy sets.

For that example, the fuzzy rule base includes rules such us the following: If the $Number\ of\ hops$ is Low and the $Battery\ Level$ is

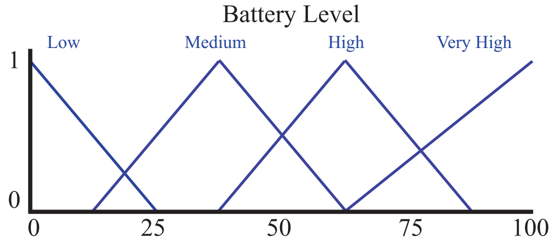


Figure 6: Battery level fuzzy sets.

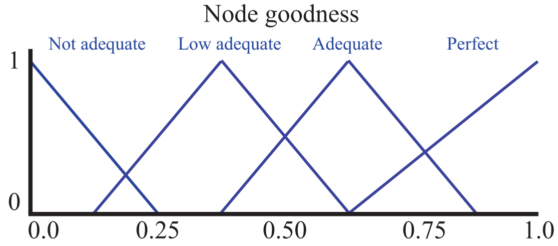


Figure 7: Output fuzzy sets defined for NORIA operation.

$High$ then the $Output$ is $Adequate$. Here, since we have 4 fuzzy sets for $Battery\ level$ input and 5 for $Number\ of\ hops$ input, we therefore have 20 rules.

5.3 Performance evaluation

In this section we study the performance of NORA and NORIA in different scenarios. A comparison with a simple tree routing protocol is also carried out. This simple tree routing algorithm operates as follows: the base station announces its presence and then the nodes that have received the base station announcement send their own announcement message and start a timer. When the timer has expired, each node chooses a parent node, basing its decision on the number of hops and the link quality information. This procedure spreads hop by hop until it reaches every network node. This approach is suitable for comparison with NORA and NORIA due to it works similarly and will be considered as a basis to evaluate the performance of our proposals.

For the evaluation, we implemented NORA and NORIA using OMNET++ [16] and the project Castalia [4]. The same simulation parameters, assumptions, and experiments as in Sec. 3.2 were used. Since the objective of these experiments is to evaluate the performance of NORIA and NORA and compare them with a simple tree routing protocol, we have used CSMA/CA to control medium access. Later on, we will combine NORIA with a synchronous MAC, SA-MAC in order to get a network which is both organized and scheduled.

Figure 8 shows the behaviour of tree creation time as a function of network size for NORA, NORIA, and simple tree routing (STR). These results show the average network organization time with a confidence of the 95%, and show a shorter organization time for the NORIA algorithm, both for grid and irregular topologies. This advantage makes the NORIA organization process more efficient than other proposals, and proves that fuzzy system execution does not mean an extra waste of time.

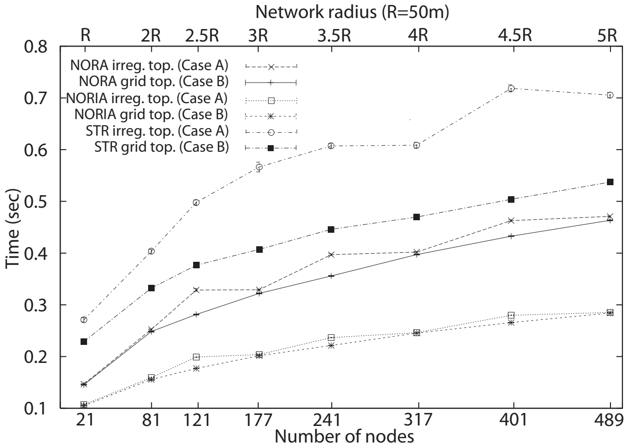


Figure 8: Network organization time.

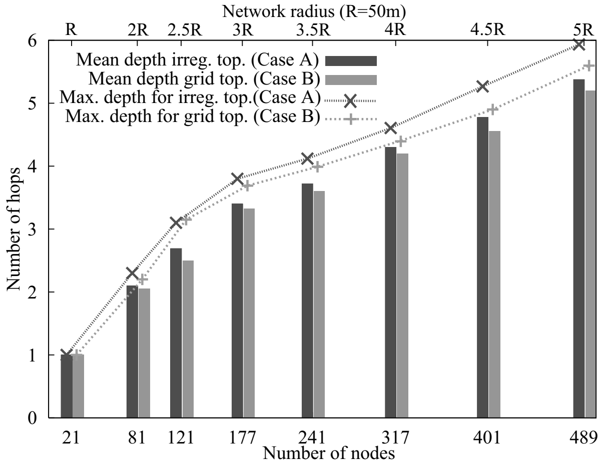


Figure 9: Max./Average number of hops (NORA).

Statistics regarding for the tree depth generated (i.e., number of hops) have also been collected. The average tree depth, in the last ring for both case A and B, is shown in Figs. 9, 10, and 11 for the NORA, NORIA, and STR algorithms respectively. Average and maximum depth for NORA and NORIA algorithms are significantly lower than the STR-created tree. This proves the efficiency in the creation of the tree when using our proposal.

The operation of NORIA has proved to be efficient both in terms of organization time and regarding the accuracy of the generated tree. Therefore, we have decided to integrate the parent-decision mechanism of NORIA with SA-MAC, in order to obtain a network in which nodes are both organized and synchronized.

6. COMBINING SYNCHRONOUS MAC WITH INTELLIGENT SELF ORGANIZATION

The integration of a synchronous MAC and an intelligent self organization algorithm will make the network more accurate and efficient.

Since SA-MAC uses just the number of hops of a neighbor to be elected as parent, integration with an efficient parent decision mechanism will be beneficial in terms of network performance and

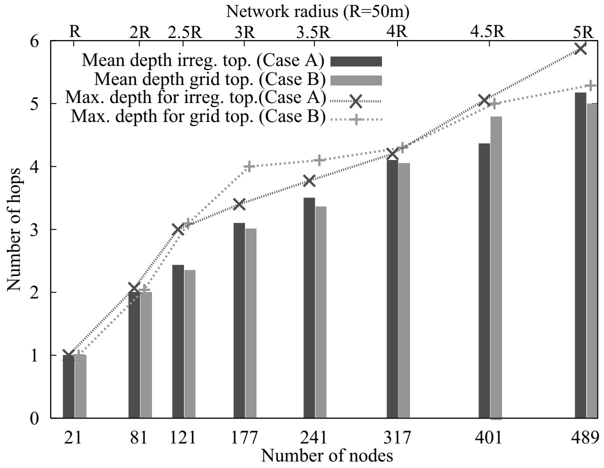


Figure 10: Max./Average number of hops (NORIA).

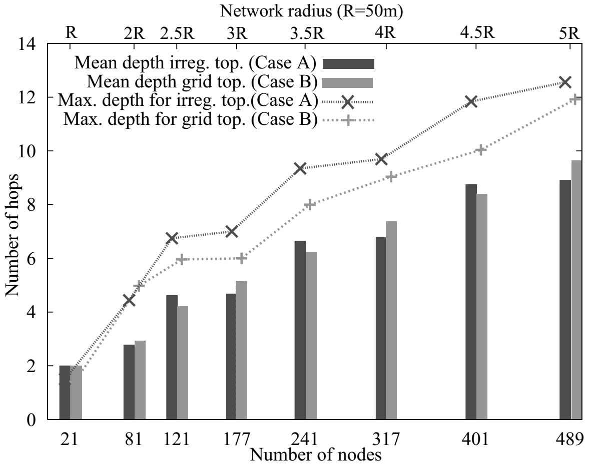


Figure 11: Max./Average number of hops (STR).

network load balance, avoiding relay-nodes overload and improving the network lifetime.

With the integration of the NORIA decision process, the aim of SA-MAC is that each node obtains an evaluation value for each neighbor node in order to select the best one. To perform this integration, SA-MAC sends to NORIA the number of hops and the battery level of the neighbor node, and the fuzzy-logic-based decision process of NORIA provides the node evaluation value. Then, the node with the best evaluation value will be selected as parent.

6.1 Performance evaluation

Using the same study cases as in the above sections, our aim is to verify that the advantages from each module have been combined.

First of all, Figure 12 shows that the addition of fuzzy logic only increments the set-up time when we are working with the grid topology, due to the fact that the nodes are frequently changing for a better parent, compared to the original SA-MAC way of working.

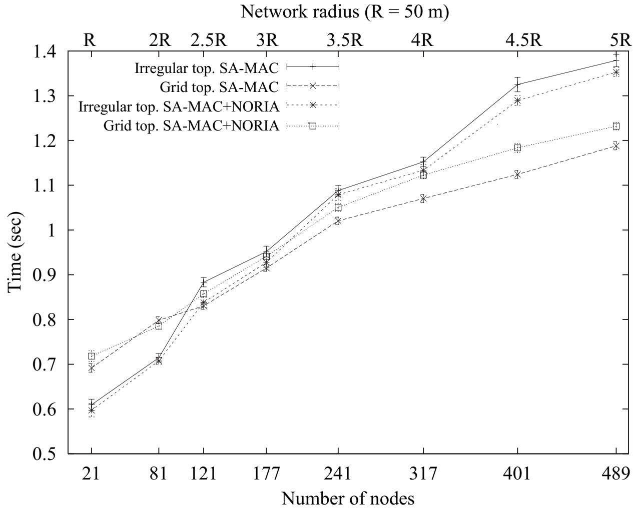


Figure 12: SA-MAC + NORIA network set-up time.

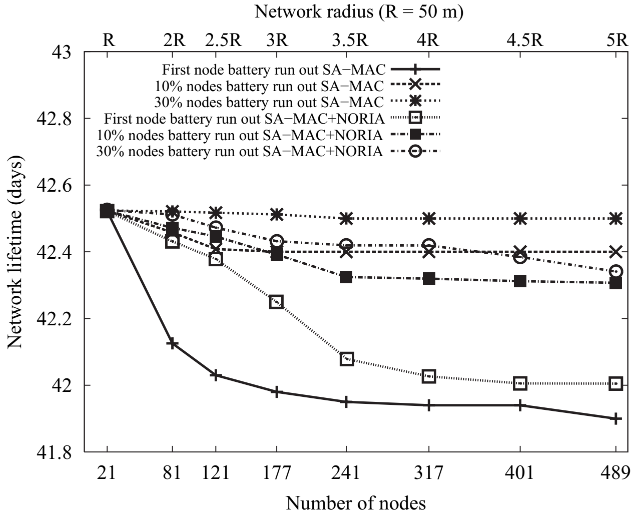


Figure 13: SA-MAC + NORIA network lifetime Case A.

The network lifetime is, in general terms, improved. For both cases (see Figs. 13 and 14), the time in which the first node's battery run out is improved, and the gap between this event and 10% and 30% of the network lifetime is reduced, indicating that network workload has been balanced correctly in the continuous process of network re-configuration. What is noteworthy is the improvement on grid topology. Although the set-up time was slightly longer, this increase is not significant compared to the balance of workload among the nodes, and so the network lifetime significantly increased.

In terms of tree depth, the combination of SA-MAC and NORIA generates trees with similar depth as the case of NORIA working alone. These tree depths confirm that the integration of both techniques makes the network more efficient, improving network lifetime.

7. CONCLUSIONS

In this paper, we have presented a new wireless sensor network design integrating an existing TDMA-based MAC protocol with NORIA, an approach for network self-organization in WSNs.

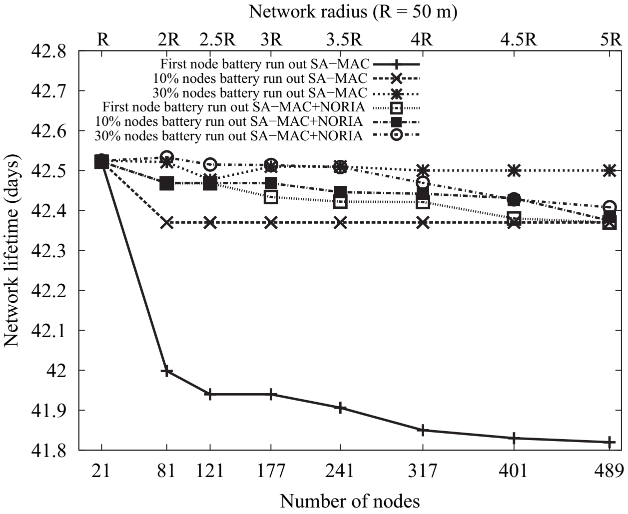


Figure 14: SA-MAC + NORIA network lifetime Case B.

Since the correct operation of a WSN requires that all nodes have to know who they have to send to, and at which moment, it is desirable that the network is both self-organized and synchronized. First of all, we have performed a deep study of previous work, and SA-MAC protocol was selected to be integrated with a fuzzy-logic-based self-organization algorithm, NORIA, which is the evolved form of a role-based algorithm.

Several experiments were performed to check both the efficiency and the performance of each protocol separately. The results of these experiments have revealed that both of them have an adequate set-up and organization time, and that the communication tree created is correct. Furthermore, NORIA has been compared to another self-organization algorithm (STR), obtaining a shorter organization time and trees with a lower number of hops. The organization of the network has been delegated to the fuzzy-logic engine, and now, the MAC protocol only has to worry about performing an efficient medium access.

Experimental results have shown that the combination of SA-MAC and NORIA reduces the depth of the communication tree, and that the network load has been balanced among nodes, thus increasing network lifetime. The integration of a fuzzy logic based mechanism to organize the network with a synchronous MAC protocol has allowed a smart network design where network nodes are both organized and synchronized.

Acknowledgements

This work has been jointly supported by the MINECO and European Commission (FEDER funds) under the project TIN2012-38341-C04-04, as well as by the EU ITEA 2 Project 11020, Social Internet of Things-Apps by and for the Crowd (SITAC).

8. REFERENCES

[1] J. N. Al-Karaki and A. E. Kamal. Routing techniques in wireless sensor networks: a survey. *Wireless Communications, IEEE*, 11(6):6–28, 2004.

[2] J. Barbancho, C. León, F. Molina, and A. Barbancho. Using artificial intelligence in routing schemes for wireless networks. *Computer Communications*, 30(14):2802–2811, 2007.

[3] A. Boukerche. *Algorithms and protocols for wireless sensor networks*, volume 62. Wiley-IEEE press, 2008.

[4] A. Boulis. Castalia: revealing pitfalls in designing distributed algorithms in wsn. In *Proceedings of the 5th international conference on Embedded networked sensor systems*, pages 407–408. ACM, 2007.

[5] F. Dressler. A study of self-organization mechanisms in ad hoc and sensor networks. *Computer Communications*, 31(13):3018–3029, 2008.

[6] D. Hristu-Varsakelis and W. S. Levine. *Handbook of networked and embedded control systems*. Birkhauser Boston, 2005.

[7] W.-H. Liao and H.-H. Wang. An asynchronous MAC protocol for wireless sensor networks. *Journal of Network and Computer Applications*, 31(4):807 – 820, year = 2008.

[8] M. Macedo, A. Grilo, and M. Nunes. Distributed latency-energy minimization and interference avoidance in tdma wireless sensor networks. *Computer Networks*, 53(5):569–582, 2009.

[9] A. M. Ortiz, F. Royo, T. Olivares, J. C. Castillo, L. Orozco-Barbosa, and P. J. Marron. Fuzzy-logic based routing for dense wireless sensor networks. *Telecommunication Systems*, pages 1–11, 2011.

[10] J. Polastre, R. Szewczyk, and D. Culler. Telos: enabling ultra-low power wireless research. In *Information Processing in Sensor Networks, 2005. IPSN 2005. Fourth International Symposium on*, pages 364–369. IEEE, 2005.

[11] Q. Ren and Q. Liang. An Energy-Efficient MAC Protocol for Wireless Sensor Networks, 2005.

[12] L. Reznik. *Fuzzy controllers handbook: how to design them, how they work*. Newnes, 1997.

[13] F. Royo, M. Lopez-Guerrero, L. Orozco-Barbosa, and T. Olivares. 2c-wsn: a configuration protocol based on tdma communications over wsn. In *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*, pages 1–6. IEEE, 2009.

[14] F. Royo, T. Olivares, and L. Orozco-Barbosa. A synchronous engine for wireless sensor networks. *Telecommunication Systems*, 40(3-4):151–159, 2009.

[15] G. D. M. Serugendo, N. Foukia, S. Hassas, A. Karageorgos, S. K. Mostéfaoui, O. F. Rana, M. Ulieru, P. Valckenaers, and C. Van Aart. Self-organisation: Paradigms and applications. In *Engineering Self-Organising Systems*, pages 1–19. Springer, 2004.

[16] A. Varga and R. Hornig. An overview of the omnet++ simulation environment. In *Proceedings of the 1st international conference on Simulation tools and techniques for communications, networks and systems & workshops*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2008.

[17] J. Wallace, D. Pesch, S. Rea, and J. Irvine. Fuzzy logic optimisation of MAC parameters and sleeping duty-cycles in wireless sensor networks. In *Vehicular Technology Conference, 2005. VTC-2005-Fall. 2005 IEEE 62nd*, volume 3, pages 1824–1828, 2005.

[18] N. Wirström. Optimization of wireless sensor networks using machine learning. *Master of Science Thesis, KTH Computer Science and Communication*, 2006.