Smart Cross-Layer Protocol Integration for Efficient Wireless Communications

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Abstract:
The integration of protocols from different layers enables efficient wireless communications. Wireless sensor networks represent the core of the Internet of Things. The growing number of nodes composing these networks requires effective node synchronization and a correct network organization in order to ensure data delivery to the destination nodes. This article presents a cross-layer approach that integrates a synchronous TDMA MAC protocol with a smart

routing approach, oriented to guarantee efficient communications of a set of wireless devices in the Internet of Things. First, both approaches are detailed and individually tested by comparing them to similar approaches in the literature. Then, the cross-layer integration is described and tested, showing that both protocols are able to enhance the network performance when working together.

Keywords: Protocol integration; cross-layer; wireless sensor networks; efficient communications; TDMA MAC protocols; fuzzy-logic based routing protocols; Internet of Things.

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1 Introduction

Efficient communications represent the ultimate objective of wireless networks. The task of sending data from a source to a destination in a reliable manner, ensuring that receivers are able to receive the data without errors, and inside the time frame required by the application, guarantees the correct operation and the final user satisfaction.

When these wireless communications are performed by energy-constrained devices, and commonly battery-powered, it is also important to reduce the energy consumption in order to extend, as much as possible, the network lifetime.

From the final application to the ultimate communication through the wireless channel, all the elements in the protocol suite need to cooperate to achieve the following goals: low energy consumption, efficiency, reliability, accuracy, collision avoidance, and minimum data loss.

The Internet of Things (IoT) aims at completely changing the shape of modern wireless communications by integrating a large set of devices in a common platform where sensors, actuators, smartphones, tablets, ID-tags, etc., can seamlessly communicate and be the basis of advanced services and applications [1]. IoT comprises a number of different communication protocols, depending on the different communication capabilities of the diverse devices. The main goal of this article is to provide a smart cross-layer design to allow efficient communications from a set of sensors to a base station that gathers their data.

This article presents a cross-layer approach that integrates two protocols for the link and network layers, oriented to guarantee efficient communications of a set of wireless devices in the Internet of Things.

Wireless Sensor Networks (WSNs) are one of the main components required for the IoT, small sensor devices that wirelessly communicate with each other, offer the possibility of seamlessly gather data from the environment, and making them available for a set of different applications. Designing an appropriate framework where topology control, routing and MAC approaches work together, is critical for the scalability and longevity of the deployed network. Nodes in a WSN need to communicate among themselves to transmit data in a single or multi-hop way to a base station [2]

The proposal presented in this article integrates MAC and network protocols that have demonstrated to correctly operate by their own, proving that the integration is able to improve even more the overall network performance. Since radio communication is the major energy consumer in WSNs, the optimization and integration of networking protocols can greatly extend the lifetime of the sensor network as a whole [3].

In the MAC layer, we consider SA-MAC (Synchronous after-Awake Media Access Control) [4], a Time Division Multiple Access (TDMA) synchronous protocol that manages the communication channel available for the nodes, and avoids collisions and transmission errors, so ensuring that data are correctly received by the destination nodes, efficiently setting-up the communication slots.

At the network level, where nodes decide where to send their data, we propose the use of NORIA (Network self-Organization Rule-based Intelligent Algorithm) [5], an intelligent routing protocol that combines different metrics in order to reduce the energy consumption while improving the data routes by selecting the most appropriate paths to send data towards the base station.

The combination of SA-MAC and NORIA will exploit the benefits of both proposals; a collision-free environment where nodes can select the best communication paths according to a set of metrics that are directly related to the routing efficiency, so improving the overall efficiency of network communications and providing the IoT services and applications with valuable data.

The remainder of this article is organized as follows. Section 2 reviews the related work. Section 3 depicts the fundamentals of the synchronous MAC protocol, SA-MAC and details its performance evaluation. Section 4 details the use of fuzzy logic for decision making. In Sec. 5 NORIA is described along with a brief performance evaluation. Section 6 presents the integration of SA-MAC and NORIA, and analyzes the overall network performance of both proposals working together. Finally, Sec. 7 presents some conclusions and future work.

2 Related work

The use of TDMA MAC protocols avoids 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 [6]. A few relevant MAC protocols that make use of TDMA channel sharing are worth mentioning in [7]. 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 [8]. 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 a set of relevant parameters that directly affect to the overall network performance.

In [9], 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 [10] and some general design paradigms for self-organized networking are proposed in [11].

There are previous protocol integration initiatives in WLAN networks, as the IEEE 802.11s standard, where mesh networking services and protocols based on the IEEE 802.11 MAC Layer are integrated [12].

The idea of using artificial intelligence techniques to help in the decision-making process in order to get more efficient algorithms constitutes the core of a number of papers: machine learning [13] or neural networks [14] 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 the 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 the efficiency and to extend the network lifetime.

A relevant study combining fuzzy rules with networking can be found in [15], 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 [16], 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.

Regarding the integration of MAC and routing protocols, MERLIN [17] a cross-layer protocol that integrates SMAC and ESR routing was a pioneer in this aspect. The joint usage of both SMAC and ESR causes high end to end delay. However, MERLIN reduces this latency yielding significant extension to network lifetime, but only in low duty cycle scenarios. Some more recent studies are present in wireless mesh networks [18], [19]. In [18] authors combine STDMA and optimum routing. Each node optimally finds the best routes over the whole network while considering routing decision by all the other nodes. They assume that all nodes have full topology information of the mesh network as well as the correct packet detection probabilities for all the links, and a reference time starting for the STDMA frames. In [19] the problem of joint routing and link scheduling in a cross-layer approach, of leaky-bucket constraints flows that request deadlines guarantees, is showed as an optimization problem.

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

3 Synchronized MAC

Considering the importance of energy consumption in sensor networks, it is worth to note that avoiding overhearing, idle listening, packet overhead and collisions will greatly help to reduce the overall energy consumption and to extend the network lifetime. According to these requirements, SA-MAC provides node synchronization to improve the performance of network communications.

3.1 SA-MAC Protocol overview

SA-MAC is a TDMA protocol for scheduling communication slots, in order to synchronize the ON/OFF periods of senders and receivers.

The operation of SA-MAC considers a network composed of a central node (sink, base station) that gathers the data sent by the rest of network nodes. Some of these nodes may have, when required, to act as relays, so enabling multihop paths in the network.

The SA-MAC protocol makes use of the superframe structure defined in the IEEE 802.15.4 standard for a beacon-enabled network. Network beacons are broadcasted by a coordinator node and they are used to synchronize the network nodes by signaling the boundaries of superframes. These superframes are divided into 16 equally-sized time slots where the first one is used as a beacon. In the case of multihop networks, the beacons are also used to identify a local coordinator as a possible relay node to the base station.

During the network operation, the network can enter into either active or inactive modes. In the inactive mode, the coordinator shall not interact with its associated nodes, and they may enter in a low-power mode. During the active mode, the operation of SA-MAC is divided into two phases: first, a setup phase that performs node discovery, and second, the synchronization and data transmission phase. During the setup phase, the nodes in the network exchange four types of packets, namely discovery packets (DSC), delay packets (DLY), and acknowledgement packets (ACK and ACKasoc). The setup phase starts when the base station announces its presence as a parent node so that all the 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.

Delay packets (DLY) indicate to the nodes the assigned time slot where they can send their data to their base station. Then, nodes acknowledge the DLY packet, and this ACK packet will be replied from the parent node with an ACKasoc, so ensuring that both nodes have correctly established the father-and-child relationship. For multihop networks, each node repeats the procedure followed at the beginning by the base station, offering themselves as relays (coordinator) to forward data coming from other nodes towards the base station.

Once the network structure has been created, the base station transmits a SYN packet indicating the beginning of the data transmission phase. This 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 N1, N2 and N3. Let us assume that N1 and N3 are located within the coverage area of the BS and that N2 is located within the coverage area N3, 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 the child nodes 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 child nodes associated to a parent, the following condition has to be met for proper synchronization:

$$t_U^f < t_U^1 < t_D^1 < ... < t_U^{n-1} < t_D^{n-1} < t_U^n < t_D^n < t_D^f \tag{1}$$

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.

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

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

analysis of the re-synchronization interval was carried out in [4]. In practice, the length of frame synchronization will strongly depend on the technology used.

3.2 Performance evaluation

This section presents the performance evaluation of the SA-MAC protocol in different scenarios. The main objective is to identify and assess the effect of different factors on the protocol performance.

SA-MAC was implemented using OMNET++ [20] and the Castalia module [21]. This simulator was selected since it is an open-source solution, which is continuously updated and widely used by the research community. 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 setup phase. Table 1 lists the most important parameters used in the experiments.

In order to test the effect of node density and network nodes spatial distribution for the setup phase, we set up the following scenarios.

- **Case A**. Irregular topology and increasing area. Nodes are randomly placed around incremental circular areas with the base station located at the center. We considered areas with different radius 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 to 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 has finalized its association procedure, so finishing the network setup.

Figure 3a shows the setup time as a function of the network size. When the network includes the nodes that are 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 the network setup time around 80-90% depending on the network size.

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.

These results show that it is feasible to use SA-MAC in large networks because its set-up phase is able to quickly schedule the slot assignment for all the nodes in the network.

The synchronization and data transmission phase is evaluated by testing 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 the Telosb datasheet [22], and the t_{guard} defined, we can calculate the maximum synchronization interval as:

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

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 selected 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.

SA-MAC does not consider any parameter to perform parent selection; it is, the first node that announces its presence is selected as parent by those nodes that have received the announcement. Hence, one may think that the consideration of relevant parameters when selecting parent nodes such as number of hops, signal strength, or battery level will improve the quality of the selected routes, so enhancing the overall network performance. For that, we have selected NORIA, an intelligent routing protocol that selects parent nodes according to a set of parameters that are combined by using fuzzy logic. The next section details the operation of fuzzy logic mechanisms and illustrates how to use it to combine different parameters for parent selection.

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 [23].

In order to evaluate a set of parameters through a fuzzy logic system, it is necessary to delimit the input and output variables into fuzzy sets, it is, map the diverse values that the parameters can take, and represent them as fuzzy sets that are aligned with a descriptor (e.g., for the distance parameter, fuzzy sets can be close, medium, and far). The different fuzzy values of the input and output parameters are then combined to create fuzzy rules in the form: IF $parameter_a$ is $fuzzyvalue_x$ AND $parameter_b$ is $fuzzyvalue_y$ THEN $output$ is $fuzzyvalue_z$.

Fuzzy rules are evaluated through an inference engine, one of the frequently-used fuzzy-logic inference methods is Mamdani [24], which consists of four phases (see Fig. 4): (i) Fuzzification: raw data is converted into natural language, that is, fuzzy values. These fuzzy values represent the membership degree of the input variables to the fuzzy sets. (ii) Rule evaluation: the inference engine evaluates the fuzzy rules to get a fuzzy output. If any fuzzy rule has more than one antecedent (conditional element), an AND (minimum) or OR (maximum) operator is used to estimate the output value of rule evaluation. (iii) Aggregation: the outputs of the different rules are combined to form a new fuzzy value. (iv) Defuzzification: the fuzzy value obtained in the previous step is converted into a number. The output provided by the Mamdani inference mechanism represents the combination of the input values.

Fuzzy logic appears as an appropriate solution to enable parameter combination and evaluation during the parent selection. Since this technique requires low computational capabilities, and it is able to get a high efficiency with a few data samples, it will be used during the parent selection process so taking advantage of the combination of different parameters.

The next section details NORIA, a routing protocol that makes use of the fuzzy logic to perform the evaluation of neighnour properties in order to select the most appropriate node as parent (i.e., relay), so creating efficient routes in the network.

5 Intelligent routing

The selection of communication paths, from sources to the destination is a key element for any network, and specially for sensor networks, where the limited available energy increases the importance of efficient routing mechanisms. The combination of several parameters allows network nodes to be able to select the most appropriate parent, so enabling the creation of network paths that fulfil the network requirements.

In this article we propose the use of NORIA, a routing protocol for WSNs which uses a decision process based on fuzzy-logic.

5.1 Fuzzy logic based routing

NORIA is a routing protocol capable of creating and maintaining a communication tree by considering different parameters that are combined using fuzzy logic.

The process of creating the tree-based logical structure starts at the base station, and it is then propagated hop by hop until covering all the network nodes. Each node evaluates its

Table 2 Fuzzy rule base

Nhops	Bat.	RSSI	Output	Nhops	Bat.	RSSI	Output	Nhops	Bat.	RSSI	Output
Low	Low	Low	**Low**	Med	Low	Low	**Low**	High	Low	Low	**Low**
Low	Low	Med	**Low**	Med	Low	Med	**Low**	High	Low	Med	**Low**
Low	Low	High	**Med**	Med	Low	High	**Med**	High	Low	High	**Med**
Low	Med	Low	**Low**	Med	Med	Low	**Low**	High	Med	Low	**Low**
Low	Med	Med	**Med**	Med	Med	Med	**Med**	High	Med	Med	**Low**
Low	Med	High	**High**	Med	Med	High	**Med**	High	Med	High	**Med**
Low	High	Low	**Med**	Med	High	Low	**Low**	High	High	Low	**Low**
Low	High	Med	**High**	Med	High	Med	**Med**	High	High	Med	**Med**
Low	High	High	**High**	Med	High	High	**High**	High	High	High	**Med**

neighbors in order to select the best one (considering the fuzzy logic based combination) as a relay toward the base station.

In order to create the communication tree, nodes executing NORIA use two kinds of messages: route decision message (RDM), and information propagation message (IPM). The process starts when the base station broadcasts an RDM; those nodes receiving the RDM will store the information in the neighbour table, will send an IPM, and will start a timer. During the timer duration, the nodes will evaluate each neighbor present in the neighbour table and any other from which they receive an RDM or IPM by using the fuzzy logic module. When the timer finishes, the node with the best evaluation will be selected as parent. Then the nodes will send an RDM to continue the route creation process, until all the nodes in the network have selected a parent node to forward their data toward the base station.

5.2 Fuzzy logic module

Routing in NORIA is based on the parent selection procedure that is performed by the fuzzy logic module. This module considers as input variables the number of hops to the base station, the residual energy, and the signal strength (i.e., Received Signal Strength Indicator, RSSI). 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 both input and output parameters.

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.

For that example, the fuzzy rule base detailed in 2 includes rules such us the following: If the $Number\ of\ hops$ is Low and the $Battery\ Level$ is $High$ and the $RSSI$ is $High$ then the $Output$ is $High$. Here, since we have 3 fuzzy sets for each input parameter, we therefore have 27 rules.

5.3 Performance evaluation

In this section we study the performance of NORIA in different scenarios. A comparison with a simple tree routing protocol (STR) is also carried out.

STR 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 NORIA due to it works similarly and will be considered as a basis to evaluate the performance of our proposal.

For the evaluation, we implemented NORIA using OMNET++ [20] and the Castalia project [21]. 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 to compare it with a simple tree routing protocol, we have used CSMA/CA to control the medium access. Later on, we will combine NORIA with SA-MAC in order to test the performance of the integration of our two proposals.

Figure 6a shows the behaviour of tree creation time as a function of network size for NORIA and 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 the execution of the fuzzy system does not mean an extra waste of time.

The results regarding the tree depth generated (i.e., number of hops) have also been collected. The average tree depth, in the last ring for both cases A and B, is shown in Figs. 6b, and 6c for the NORIA and STR protocols respectively. Average and maximum depth for the NORIA protocol are significantly lower than the STR-created tree. This proves the efficiency of NORIA in terms of tree creation, as well as the benefits of using fuzzy logic for the parameter combination.

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. The next section details this union, showing how the different mechanisms have been integrated, as well as a deep performance analysis of the cross-layer approach.

6 Cross-layer protocol integration

During the operation of wireless networks, nodes must select the most appropriate time slot and the adequate next hop, in order to try to exploit, as much as possible, the resources of the network. In this article, we propose the integration of a synchronous MAC protocol, to allow nodes to exactly know when to send data packets, and an intelligent routing protocol to select the best relay node by considering a set of relevant metrics, so enabling the network to operate in an efficient fashion, wisely using the limited resources of sensor nodes.

Both proposals, SA-MAC and NORIA have been detailed in the previous sections. Their integration will bring benefits for both of them:

- SA-MAC efficiently schedules the time slots in which nodes have to send their data, but only considers the number of hops to select the parent nodes. Hence, the integration with NORIA will bring more accuracy in the selection of the parent nodes by considering an intelligent combination of the routing parameters.
- NORIA constitutes an efficient approach for the routing layer, but without an efficient MAC mechanism, many collisions and data loss may occur, so degrading the advantages of a good parent selection procedure.

With the integration of both proposals, SA-MAC obtains an evaluation value for each node in order to select the best possible parent, and NORIA takes advantage of the collision-free environment brought by SA-MAC. To perform this integration, SA-MAC sends to NORIA the number of hops, the battery level and the RSSI of each 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. This procedure that starts at the base station, finishes when all the network nodes have selected a parent, so they have a path toward the base station, that stores the data coming from all the network nodes to perform further analysis.

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 kept, and check how the cross-layer integration of SA-MAC and NORIA improves the overall network performance.

The network set-up time for the cross-layer integration is shown in Fig. 7a. The addition of the fuzzy-logic mechanism does not represent extra load for the system, with slightly differences between cases A and B; when the network size is small, the the network setup is faster in the case of the irregular topology, due to nodes may be located in small groups, so many of them can select their parents at the same time. In contrast, when increasing the network size, the grid topology performs better, since those small groups become bigger and the collision avoidance mechanism makes them to wait to get a free slot to send the parent request.

In terms of network depth (see Fig. 7b), the integration of SA-MAC and NORIA does not significantly increase the depth of the generated trees. It is worth to note that the minor differences in terms of tree depth with the results presented in Fig. 6b, are due to the scheduling procedure introduced by SA-MAC, that makes that some nodes do not receive the information about all their neighbors. This trade-off between set-up time and tree depth can be configured depending on the specific application needs. For the results presented herein, the same waiting time as in the case of the evaluation presented in Sec. 5.3 has been used.

The cross-layer integration improves, in general terms, the network lifetime. In the case of the irregular topology (Case A, see Fig. 8a), the time in which the first node's battery runs 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. Moreover, the lifetime improvement on grid topology (see Fig. 8b) is highly remarkable. Thanks to the equidistant node location, the network is able to efficiently balance the load and make that most of the nodes run out of battery in a very short period of time, so extending the operational network lifetime.

The experiments related above represent an application with particular needs where the number of hops, the residual battery level and the RSSI were relevant. The fuzzy-logic-based evaluation system can be configured with other necessary variables in case of applications with other specific requirements, so making the presented approach adequate for a variety of applications in the IoT framework.

7 Conclusions

The correct operation of the IoT relies on the effective communication among devices. Thus, cross-layer integration remains a key aspect in the success of this technology.

This article has presented a cross-layer approach that integrates a synchronous MAC protocol, that efficiently synchronizes the network nodes, with an intelligent routing approach that considers several relevant metrics to select the next hop in sensor communications.

Integrating MAC and routing approaches enables the network to work more efficiently. In the MAC layer, SA-MAC is able to schedule nodes communications, so avoiding collisions and data loss. NORIA in the network layer selects the best next hop by considering a set of parameters that are combined through fuzzy logic, and that can be customized for each particular application.

Both proposals have been presented and tested separately to later integrate them and test the performance of the whole system working under the cross-layer integration. In general terms, both approaches perform well when working alone, and, what is more important, their integration is able to improve even more the overall network performance, and to extend the network lifetime.

The proposal presented herein represents the first step to create a fully functional communication approach for devices in the IoT, that can be adapted to the specific requirements of a variety of applications for this new paradigm.

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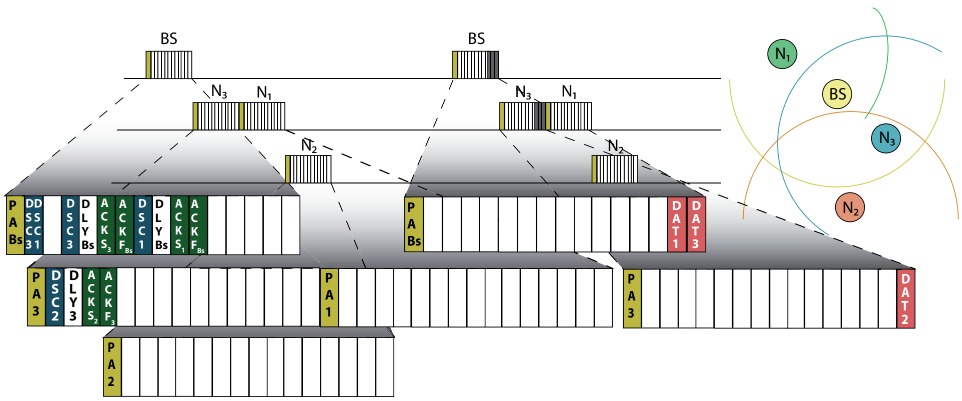


Figure 1: SA-MAC setup phase.

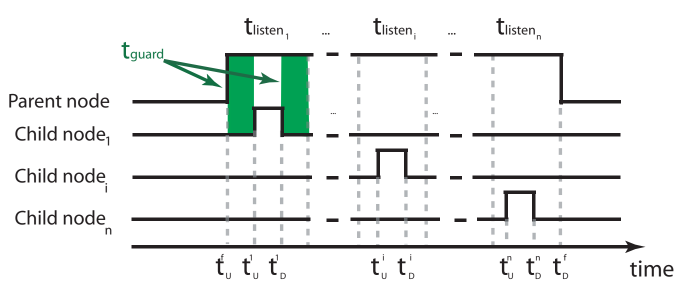
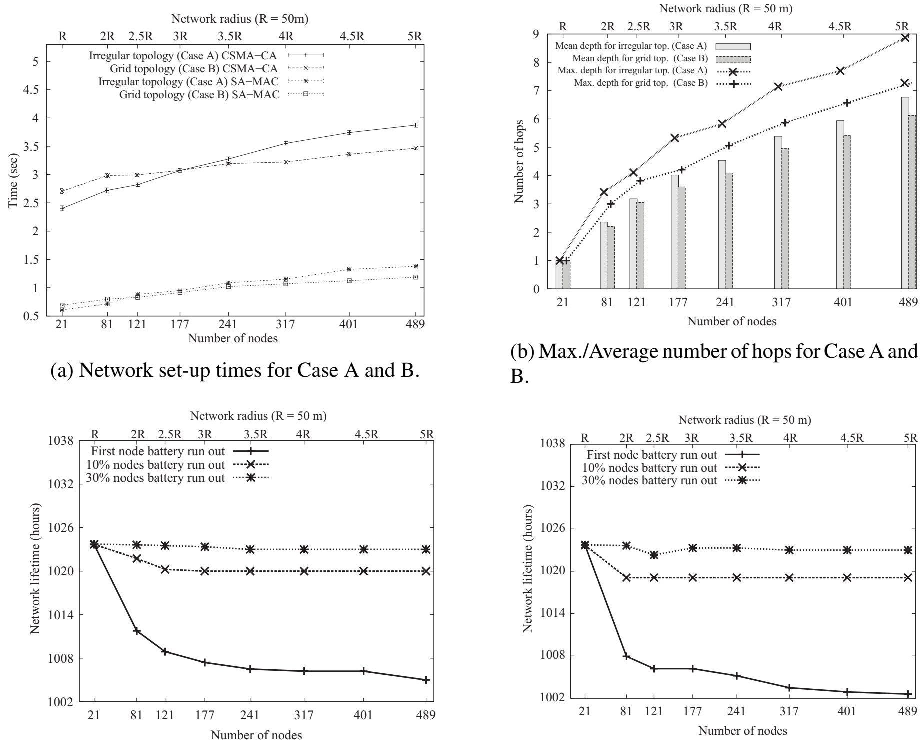


Figure 2: Time wise synchronization.



(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 .

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

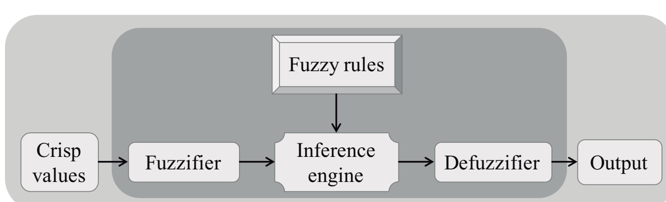
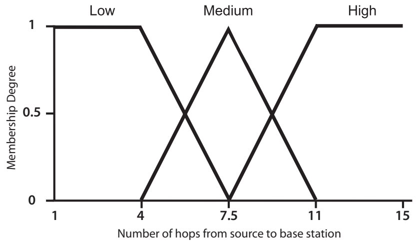
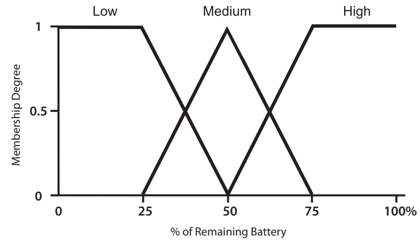


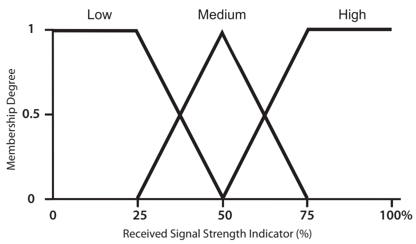
Figure 4: Mamdani fuzzy logic system.



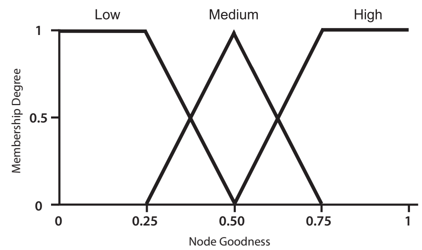
(a) Fuzzy sets for number of hops to the base station.



(b) Fuzzy sets for residual energy level.

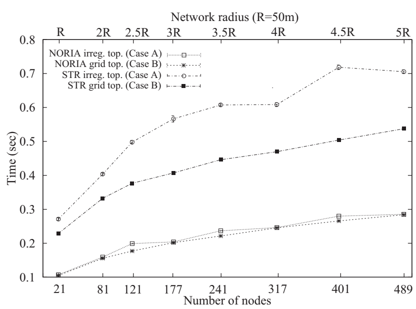


(c) Fuzzy sets for signal strength (RSSI).

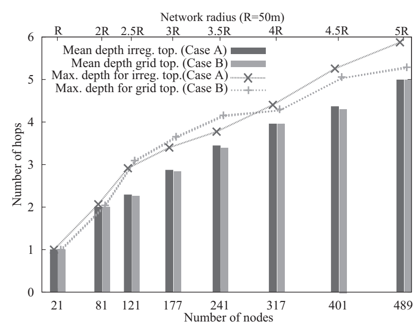


(d) Fuzzy sets for the output metric.

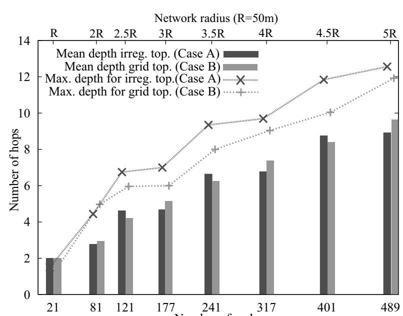
Figure 5: Fuzzy sets for input and output parameters.



(a) Network organization time.

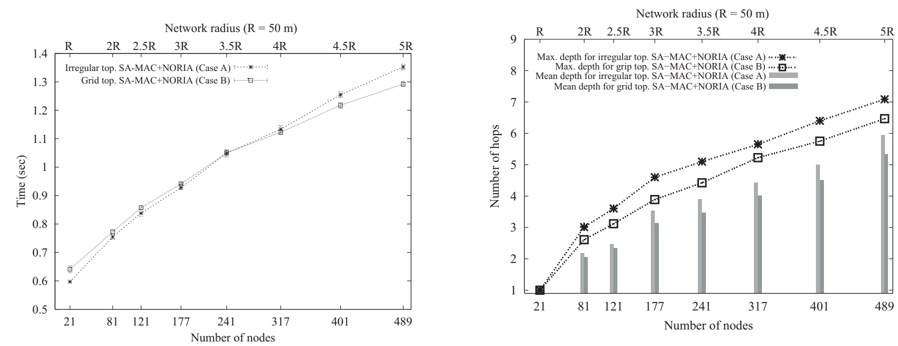


(b) Max./Average number of hops (NORIA).



(c) Max./Average number of hops (STR).

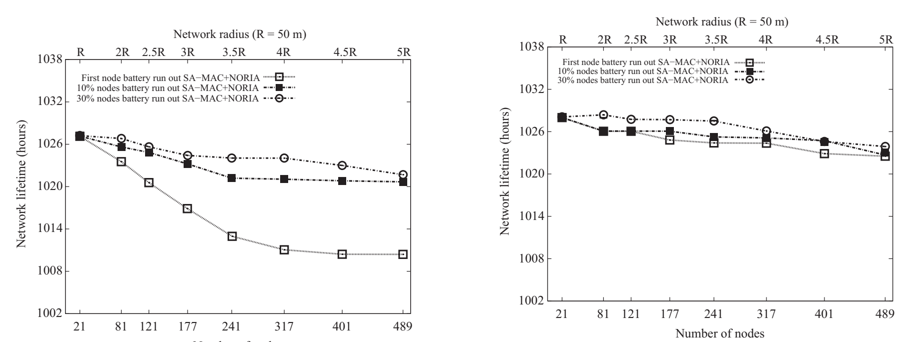
Figure 6: Performance obtained using NORIA comparing with STR.



(a) SA-MAC + NORIA network set-up time.

(b) Max/Average number of hops (SA-MAC + NORIA).

Figure 7: Set-up time and network depth when using the integration of SA-MAC and NORIA.



(a) SA-MAC + NORIA network lifetime Case A.

(b) SA-MAC + NORIA network lifetime Case B.

Figure 8: Network lifetime for the integration of NORIA and SA-MAC.