Applying fuzzy logic for decision-making on Wireless Sensor Networks[1]

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Abstract— **We propose a fuzzy-based decision-making mechanism for selecting data dissemination protocols in wireless sensor networks (WSNs). Its goal is to select the most efficient protocol considering network performance and application-specific requirements. The mechanism relies on performing simulations and on defining and executing a two-tier fuzzy system. First, well-known WSN protocols are simulated over different scenarios and application requirements to feed a knowledge base. Then, a set of fuzzy systems are built based on the simulation results. A methodology for guiding the building of the knowledge base was developed. A case study is described to validate the mechanism and demonstrate its employment and usefulness.**

I. Introduction

Wireless Sensor Networks (WSNs) are distributed systems composed of hundreds to thousands of multifunctional sensor nodes endowed with limited sensing, computing and wireless communication capabilities. Since sensor nodes are often battery-operated, once deployed they work until the energy is depleted. Given the high density of typical WSNs and their deployment in remote or hostile areas, manual replacement of nodes is unfeasible. Therefore, the network lifetime is dictated by the duration of individual nodes, making the energy saving a crucial requirement.

One major reason for the increasing academic and commercial interest in WSNs in the last few years is their potential employment for a wide range of application areas such as health, surveillance, environmental monitoring and others [1]. Most of WSN applications are based on the collection of data by sensor nodes (sources) and on the data forwarding, often through multiple hops, towards one or more exit points, called sink nodes. The paths from sources to sink nodes are established and managed by data dissemination protocols. Several WSN protocols have been proposed in the last few years, with the main goal of minimizing the consumption of energy in the network.

The nature of the WSN applications has strong impact on the network resource consumption. WSN applications have different features and QoS requirements [8], demanding different data delivery models, logical network topologies and data dissemination protocols. Therefore, each protocol is more suitable for a specific set of scenarios and application requirements and its implementation is often strongly coupled to the application code. Such approach results in energy-efficient, however rigid WSN systems.

According to recent works [8][9], the choice of the data dissemination protocol to be adopted in the WSN directly influences on the network global performance, in terms of both energy consumption, and user satisfaction. Therefore, a mechanism that selects the most appropriate parameters for WSN configuration (topological organization, number of active nodes and dissemination protocol) in a transparent way for application developers would be a useful tool for leveraging WSN application development, while optimizing the usage of the network resources.

We propose a novel decision-making mechanism to automatically select the data dissemination protocol that better meets application-specific requirements while minimizing the network resource consumption. The proposed mechanism receives as inputs user known parameters, including the number of sink and sensor nodes, the description of the sensing task and QoS requirements. Some of these parameters can be precisely defined by the user. However, there are parameters, in particular concerning QoS requirements, which are vaguely or imprecisely defined or, yet, specified as intervals. To address the imprecise nature of such parameters, we adopted fuzzy logic [11] as an intelligent reasoning method for selecting data dissemination protocols in the design of the decision mechanism.

The decision-making process of our mechanism relies on a set of fuzzy systems. To build these systems, a knowledge base was created and populated with simulation data. Extensive simulations of well-known WSN protocols were executed for different network scenarios and application requirements. After building the mechanism and populating the knowledge base, a set of experiments was conducted to demonstrate its feasibility and usefulness.

The main contributions of the proposed decision-making mechanism are three fold. The first contribution is the construction of a novel decision-making mechanism for WSNs. The proposed mechanism can be a useful tool to aid the design of WSN applications and to manage the existent tradeoffs among performance and application requirements. The adoption of fuzzy logic provides a suitable solution for dealing with imprecise input parameters, commonly needed for WSN applications as well as for guiding the decision process along the several options for WSN configurations. Second, we propose a hierarchical organization of multiple fuzzy systems that prevents the problem of manipulating a

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large amount of fuzzy rules in a single fuzzy system, making the process of generating fuzzy rules easier to be conceived and more understandable. Third, a methodology for building the knowledge base was developed which is generic enough to be applied in other domains, whenever there is an available set of simulation data to compose the base, a set of decision rules and a set of fuzzy parameters.

This work is organized as follows. Section II gives an overview on WSNs. Section III presents related works. Sections IV and V detail the proposed mechanism and the methodology for building the knowledge base. Sections VI and VII describe the execution of the mechanism and an example scenario. Finally, Section VIII concludes the work.

II. Overview on WSNs

The design of WSN applications is not only highly influenced by the scarcity of node resources but also by the communication model and application-specific requirements. The **communication model** in WSNs comprises (i) the data *delivery model* required by the application, which defines the strategy for triggering the data sending, and (ii) the data *dissemination protocol*, which defines the strategy for disseminating sensor data from source to sink nodes.

According to the data *delivery model*, WSNs can be classified in four types [9]: (i) continuous, in which sensors send their data continually at a predefined rate; (ii) event-driven, when sensors send data only if an event of interest occurs; (iii) request-reply, when sensors send their data in response to an explicit request from the application; and (iv) hybrid, when the three approaches coexist in the same network. Each data delivery model is tailored for different application interests and dictates the best type of data dissemination protocol to be adopted. Regarding the *data dissemination protocols*, three well known data dissemination protocols are: LEACH [4], MTE and the Direct Diffusion variants: TwoPhasePull (2PP), OnePhasePull (1PP), Push, Gear-Push and Gear-TwoPhasePull (Gear-2PP) [3].

LEACH protocol adopts a hierarchical topologic organization for the network, in which sensor nodes are organized in groups or clusters, and each cluster has a leader which forwards data to the sink node. ***MTE*** is not properly a dissemination protocol; instead it consists of the direct sending of the collected data to the sink node, without traversing intermediary nodes. ***Directed Diffusion (DD)*** adopts a flat network hierarchy and it introduces the idea of path reinforcement to establish the route for sending the data from sources to sink nodes. The authors of the protocol designed several variants of the original algorithm, each one target to a particular application class. In the ***two-phase pull variant (2PP)***, the data collecting and sending are initiated by sink nodes. The authors argue that 2PP variant fits well for applications having a small number of sink nodes. In the ***push variant***, sinks act as passive entities and source nodes periodically send data messages. This variant is target to applications that typically have several nodes interested in data and many that actually can provide such data, but the frequency of data collection and sending is sporadic. The ***one-phase pull (1PP) variant*** aims to minimize the broadcast phases of the 2PP. In this variant, only interest messages are flooded in the network. Two additional extensions where proposed, ***GEAR-2PP*** and ***GEAR-Push***, in which the node geographic location is considered in the message forwarding strategy.

The design of WSN applications is also highly influenced by ***application-specific requirements*** that are defined through the application interest. Application interest is the starting point from which the data collection takes place and it comprises the description of the sensing task along with QoS requirements. Examples of QoS requirements for WSN application are delay, packet loss, and energy consumption. Such requirements often present conflicting behaviors, that is, when one is maximized the other is naturally minimized. Therefore, there is a tradeoff to be addressed in order to manage conflicting QoS requirements.

III. A Literature Review

Currently, there are few works that address the issue of decision-making in the context of WSN applications. The first discussion on the need of fitting the data dissemination protocol to the application requirements was presented in [3]. In such work, the authors argue that, as most of the WSN protocols are optimized for specific applications, it is not feasible that only one protocol fits all the applications. Instead, a “family of protocols" should be designed, in which each protocol meets the needs of one application class. Based on this argument, the authors change the original Directed Diffusion protocol [6], generating two new versions of algorithms (push and pull), each one optimized to different scenarios and application requirements. The work shows, through simulations, that the choice of the most appropriate protocol for an application can increase the network performance in up to 60%. Differently from our proposal, the work in [3] only considered the variants of the Directed Diffusion. Besides, the work does not supply any mechanism to aid the user decision-making.

The work in [2] considers WSN applications for which both the energy consumption and the source-to-sink delay in data dissemination are crucial requirements and discusses the tradeoff between these two metrics, in order to increase the WSN lifetime. The lower and upper bounds on these metrics are computed and the work provides guidance on how to efficiently trade the energy consumption and the source-to-sink delay. Similarly to our mechanism, such work can be a useful tool to aid the application developer in his decisions. The goal of the work in [7] is similar to ours, but its approach is different. In such work, a framework is described for modeling WSNs based on generic features, identified through the analysis of existent networks. This framework helps in the modeling of new WSNs, characterizing them with templates and supplying a set of performance metrics associated to each application class. The specification of the performance requirements for each network enables the selection of the appropriate communication protocol. The fitness of a protocol for specific scenarios combines its features with parameters that describe the network (topology, number of sinks and node mobility). The proposal is based on analyses of results previously described in the literature and new simulations were not performed. The adopted approach to select the protocol is completely different from ours since it considers only discrete values to indicate whether a protocol is appropriate or not to a given scenario, while our approach is based on fuzzy logic, allowing imprecise values to be considered when defining application requirements. Therefore, our work contemplates scenarios used by WSN applications in a more realistic way.

IV. Description of the Proposed Mechanism

The main goal of the proposed decision-making mechanism is to select the most efficient protocol among a set of available ones. To fulfill this goal, the mechanism takes the description of a given network scenario and a set of application QoS requirements as its input. Some input parameters have crisp values, such as the number of nodes in the target area and the data delivery model (defined according to the description of the sensing task) while others, such as performance or QoS metrics, can be defined either in terms of minimum and maximum threshold values, or in a very non-crisp way (for instance, the network lifetime). Furthermore, the application may prioritize some parameters in detriment of others. For example, in a WSN designed for battlefield applications, the *delay* of sensor-collected data is more critical than the *energy consumption*.

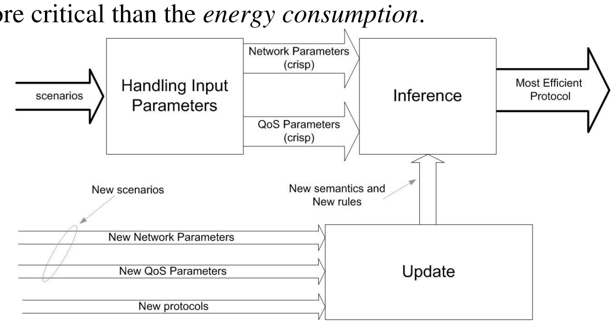

Fig. 1. Main components of the proposed mechanism

The proposed mechanism is composed of three main modules: *Handling Input Parameters Module, Inference Module* and *Update Module* (see Fig. 1). The ***Handling Input Parameters Module*** is initially responsible for verifying if the values of the input parameters (network and QoS) fit inside the upper and lower boundaries of the values contained in the mechanism knowledge base. Afterwards, this module converts fuzzy input parameters into crisp parameters. Finally, it verifies if the combination of the input parameters is a valid one. The ***Inference Module*** uses the parameters delivered by the ***Handling Input Parameters Module*** to infer the most efficient protocol among the protocols considered during the conception of the mechanism. It is composed of a set of fuzzy systems (*if-then* rules that map crisp input values in crisp output values) and the Refinement Sub-Module.

The set of fuzzy systems constitutes the kernel of the decision-making mechanism. Each fuzzy system is assigned to a network scenario and incorporates the behavior of the simulated protocols in such scenario. A network scenario is defined by network parameters and by the data delivery model required by the application. The adoption of multiple fuzzy systems prevents the problem of handling a large amount of fuzzy rules in a single fuzzy system, making the process of generating fuzzy rules easier to be conceived and more understandable. The large number of fuzzy rules is a result of the combination of fuzzy variables and their labels. These fuzzy variables are directly associated with the network and QoS parameters which characterize the investigated scenarios.

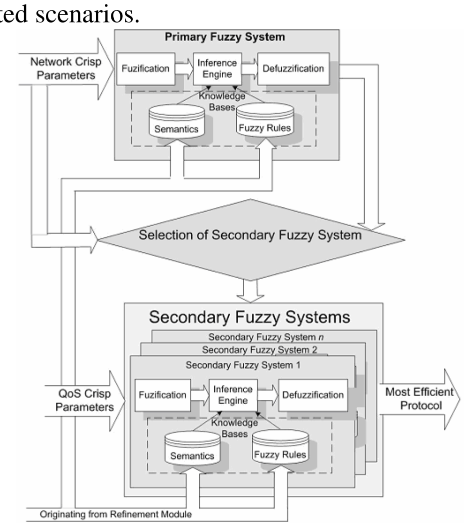

Fig. 2. Inference Module

The ***Inference Module*** encompasses a Primary Fuzzy System and a set of Secondary Fuzzy Systems (Fig. 2). The Primary Fuzzy System receives as inputs only network parameters while the Secondary Fuzzy System receives only QoS parameters. The Primary Fuzzy System is responsible for selecting, among the set of Secondary Fuzzy Systems, the one that best represents a given network scenario. The selected Secondary Fuzzy System is responsible for selecting the most efficient protocol, according to the application requested QoS requirements. This choice relies on data stored in a knowledge base that manages both semantics information and fuzzy rules. In addition, the Inference Module includes a ***Refinement*** sub-module that increases the reliability of the mechanism, minimizing the decision errors. Decision errors can occur since specific values for network and QoS parameters, which describe a given application scenario, may not be contemplated in the knowledge base. The refinement module identifies the possible discrepancies between the mechanism generated results and those obtained by human analysis of the simulation results for a given scenario. If there are discrepancies, the mechanism provides adjustment procedures that update the semantic base and fuzzy rules. Therefore, this module can be used to validate scenarios not completely specified in the knowledge base or when the knowledge base was not completely validated.

The Update Module methodically updates the knowledge bases of the fuzzy systems. This update can be accomplished by the inclusion of new fuzzy systems or by changing existent systems. The execution of the Update Module is necessary in the following cases: (1) insertion of new data dissemination protocols; (2) insertion of new network parameters; and (3) insertion of new QoS parameters of a given application.

The environment used for implementing the mechanism modules was MATLAB 7.0.

V. METHODOLOGY FOR BUILDING THE KNOWLEDGE BASE

The mechanism knowledge base comprises a semantic base and a set of fuzzy rules. The methodology for building the base encompasses five stages: (i) bibliographical research on WSNs data dissemination protocols; (ii) selection of network and QoS parameters to be used in the mechanism; (iii) planning and execution of simulations and analysis of results; (iv) definition of linguistic variables and (v) definition of fuzzy inference rules.

The *first stage* of our methodology consists of an extensive research on well-known WSN protocols in order to choose the set of protocols to be considered for the mechanism design. In the current version of our work we included the protocols: LEACH [4], MTE, and several variants of the Directed Diffusion [6] [10] [3].

The *second stage* consists of selecting network and QoS parameters. The network parameters adopted in our work include the data delivery model (periodic and event-driven) and WSN physical characteristics, such as: size of the target area; number of sensor nodes deployed in the area; distance between the sink node and the center of the target area. A derived parameter, network density, is also considered, and it is calculated as the ratio of the amount of sensor nodes in the target area to the size of the area. Three QoS parameters are considered: delay, average dissipated energy (directly related to the network lifetime) and percentage of packet loss. Delay is defined as the elapsed time from the sent of a packet by a sensor until its reception by the sink, while the dissipated energy is computed by dividing the total energy spent in the network by the amount of packets correctly received by the sink. The percentage of packet loss is calculated by the ratio of the total data packets sent by the sensor nodes to the total data packets received by the sink node.

The *third stage* consists of performing extensive simulations to analyze the behavior of the selected data dissemination protocols. A set of scenarios was planned to encompass both periodic and event-driven data delivery models. A scenario is characterized by a choice of a data delivery model and a pair of values for density of nodes and distance from the sink node to the center of the target area. The protocols behavior was analyzed regarding the three QoS parameters considered in this work. A detailed discussion on the simulation performing and results are out of the scope of this paper.

The *fourth stage* is responsible for building the mechanism semantic base, that is, for populating the knowledge base for each fuzzy system. The bases are built from data generated in the simulations performed in the second stage. The first step for building the semantic base is the definition of all the linguistic variables of both primary and secondary fuzzy systems. We assumed that the linguistic variables are defined [5] through a quintuple (X, L, U, G, M), where X is the variable symbolic name; L is the set of labels assumed by X; U is the universe of discourse that contains all possible values assumed by X; G is the syntactic rule, usually defined in the form of a grammar; and M are the semantic rules that define the meaning of each label L (also known as *membership function*). To simplify the G-grammars definition we adopted the approach based on the use of an ordered structure of linguistic terms, presented in [5]. Therefore, according to such approach, we supply directly the sets of primary terms (also known as fuzzy sets or sets of labels), distributed over a scale on which a complete (total) order is established.

For the primary fuzzy system, two linguistic variables were defined, representing the density of sensor nodes and the distance from the sink to the target area. They were labeled as *density* and *distance*, respectively. For *density*, the grammar G is given by $G_{density}$={s_0=Very Small, s_1=Small, s_2=Medium, s_3=Large, s_4=Very Large} and the five labels were defined as Very Small (VS), Small (S), Medium (M), Large (L) and Very Large (VL), in order to represent the five simulated densities. For distance, the simulation results showed that close distances present quite similar behavior for the considered performance metrics and therefore, the six values simulated were grouped in sets of two, and only three labels were defined: Small (S), Medium (M) and Large (L).

The universes of discourse for density and distance were defined considering the closed interval of real numbers between 0 (zero) and the largest simulated value for these variables, respectively, (0, 0.03) and (0, 140).

Regarding the semantic rules (membership function), they determine the shapes that represent each fuzzy set. The triangular shape was chosen for density, except for its extremities for which trapezoidal shapes were chosen. The trapezoidal shape was also chosen for distance. Thus, for each delivery model, fifteen secondary fuzzy systems are necessary, as a result of the combination of the five density labels with the three distance labels.

For building the secondary fuzzy systems, three linguistic variables were created, named *delay*, *dissipation* and *loss*, representing the respective QoS parameters. For the definition of these variables, we established that the second element of the quintuple (set of labels) is a function of the observed behavior of the simulated protocols. The universe of discourse and its shape should be defined for each QoS variable. The threshold values of each fuzzy set, for each linguistic variable, should also be defined. The definition grammar G is also based on the approach used in [5]. In the adopted methodology, each fuzzy set (term set) of the secondary fuzzy systems represents the behavior of one protocol (or more than one, if they show similar behaviors) and its membership function is graphically represented by a trapezoidal shape.

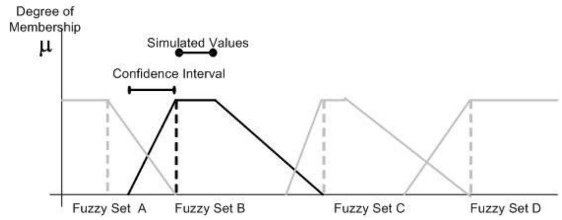

Fig. 3. Secondary Fuzzy System – Membership Function

The boundaries of the polygonal are defined as follows: the value representing the adopted confidence interval (95%) for each protocol (or set of protocols) on the left side (lower boundary) and the smallest simulated value whose membership degree in the next fuzzy set is equal to 1, on the right side (upper boundary) (Fig. 3). For a given variable, each fuzzy set must have an intersection with its next fuzzy set. So, a given value belonging to its Universe of Discourse will be contained in, at least, one of its fuzzy sets.

The next stage in generating the knowledge base consists of building the inference rules that relate the linguistic values of the fuzzy variables. Fuzzy sets of the linguistic variables are related through logic operators, as in the statement: "if density is VL *and* distance is S then 1". Once the fuzzy variables were defined, the inference rules for each fuzzy set are built taking into account the correlation between the fuzzy sets and the behaviors of the simulated protocols.

VI. Executing the Decision-Making Mechanism

When executing the decision-making mechanism, once the user provides the number of nodes, the size of the target area and the location of the sink, it is possible to calculate the node density and the distance from the target area to the sink. At this point, a validation of the input values is provided by the Handling Input Parameters Module. The Primary Fuzzy System takes as inputs the computed values of density and distance along with a given data delivery model and its execution selects the Secondary Fuzzy system to be processed. Once the secondary fuzzy system is selected, and the fuzzificated input values representing the application QoS metrics (delay, energy consumption and packet loss) have been received, the fuzzy rules evaluator identifies the rules activated by these input values. The activated rules select the most appropriate protocol for the application, among those considered by the mechanism. Finally, the defuzification process determines the crisp output, which represents the protocol with the highest value of membership degree for the provided inputs. Such protocol is reported as the final output of the decision-making mechanism. Whenever more than one protocol present equal values of membership degree, the mechanism chooses the one with the smallest value of dissipated energy.

VII. Example Scenario

The validation of the proposed mechanism was based on the execution of several case studies, exploring different WSN scenarios. Such scenarios had not been simulated in the mechanism design phase, in other words, they do not compose the system knowledge base. The case studies have the goal of demonstrating the ***capacity of inference*** of the mechanism. This was done in two phases: (i) the mechanism was executed considering each example scenario and a chosen protocol was obtained; (ii) simulations were carried out for the same scenarios and for all the investigated protocols. After that, the mechanism was validated, by comparing the protocol recommended from the decision-making process with the most suitable protocol achieved from the human interpretation of the simulation results.

In deployed WSNs a scenario is comprised by a given number of sensor nodes in operation and a number of sink nodes to extract data from the network. In addition, each scenario is intended to be used by developers of a specific application domain. Consider a case study related to an application for environmental monitoring in which developers are interested in monitoring a given set of physical parameters (temperature and solar incidence, for instance), inside of a geographical area. Since such developers are experts in their knowledge area, they are able to precisely define the geographical place they want to monitor, the duration time of the monitoring and the time interval in which they want to receive the sensor-collected data. Besides, they are able to define - not so precisely - some QoS parameters: the network lifetime (for instance, long), the maximum delay for data reception (for instance, below a given threshold), and the degree of data loss the application tolerates (for instance, very low). Since we consider dynamically configured WSN, sensor nodes can be logically organized in different ways (flat or in clusters) by exchanging configuration messages, even if the WSN is already in operation.

To illustrate how the proposed mechanism can help developers in the WSN configuration, following we describe a case study where the monitoring application (described above) runs in a deployed WSN, which consists of 230 sensor nodes scattered in an area of 100m x 100m, with one single sink node placed at 141m of distance from the center of the area. As a first step, once the values of density and distance from the sink are already defined, the proposed mechanism was executed considering all the possible options of QoS parameters, for energy consumption and for packet loss, while the maximum delay was set to 500ms.

As previously described, each fuzzy system of the mechanism considers the data delivery model, which is a crisp variable, and two linguistic variables: the density and the distance from the sink to the target area. For density, five labels were defined and for distance only three. Then, for each data delivery model (periodic/event-driven) fifteen machines were defined, encompassing all possible combinations of values. Therefore, the first decision to be taken is to choose the specific inference machine to be used in the case study. This decision is based on the number of active sensor nodes, on the sink location and on the data delivery model to be adopted. In this case study, the application required a periodic data delivery model (continuous monitoring) and the selected inference machine to be used by the mechanism was defined for the label ***Very***

Large x Large. Afterwards, the mechanism uses the informed QoS parameters to run the selected Secondary Fuzzy System and to infer the more suitable protocol. In this example, we initially execute the mechanism considering all the possible options of QoS parameters and fixing only the maximum value for delay. The obtained results are as follows: (i) considering the energy consumption and the percentage of packet loss as ***non relevant*** parameters: the best protocol was *OnePhasePull* (1PP); (ii) considering the energy consumption as ***non relevant*** parameter: the best protocol was 1PP, regardless the values for the acceptable packet loss; (iii) considering the packet loss as ***non relevant*** parameter: the best protocol was MTE, regardless the acceptable values for energy consumption; (iv) considering as relevant both the energy consumption and the packet loss, results are in Table I.

TABLE I.

RESULTS OF THE MECHANISM EXECUTION

ENERGY CONSUM	PACKET LOSS				
	VERY SMALL	SMALL	MEDIUM	LARGE	VERY LARGE
VERY SMALL	NA	MTE	MTE	MTE	MTE
SMALL/MEDIUM/ LARGE/ VERY LARGE	1PP	MTE	MTE	MTE	MTE

When analyzing the simulations results, a high correlation was observed between the protocol performance and its fitness to the application requirements. Although there are protocols which are the most suitable for the energy consumption metric, they do not present the same performance for the delay metric, for instance. Analyzing all the possible options for the achieved performance for each protocol, the developer can establish several tradeoffs and adjust his requirements to the expected behavior, before running his application.

To show the remaining steps for using the proposed mechanism in a real scenario, the example was complemented with the application QoS requirements. From the previous description, the monitoring application requires: ***maximum delay*** of 500*ms*; ***low*** energy consumption (inferred from the requirement: long lifetime for the network) and a ***very small*** packet loss. When executing the mechanism with those set of parameters, the result was the 1PP protocol. On the other hand, when analyzing the results of the simulation for this scenario, it was verified that, to attend to the delay requirement only, 1PP, MTE and Gear-2PP protocols could be used. To guarantee small energy consumption, LEACH, 1PP and MTE protocols could be used. To guarantee very small packet loss, only 1PP protocol could be used. However, when considering all the requirements together, that is, the intersection of the resulting protocols of each requirement, the protocol that better meets the user needs is 1PP protocol.

Therefore, the soundness of the result supplied by the mechanism is confirmed, since it was capable of providing the user with the most appropriate protocol, considering the specific needs of his application.

VIII. CONCLUSIONS

We presented a Fuzzy Logic based decision-making mechanism which chooses the most suitable data dissemination protocol for a given application in the WSN domain. In our work, the definition of a scenario encompasses all the important features to represent a WSN to be used by a specific application class. We considered that the parameters chosen to define a scenario can fully specify a given WSN behavior. However, the mechanism allows that new parameters can be included to characterize a WSN.

The issue of choosing which protocol to use and how to improve its performance for a given application is important since there are some tradeoffs between different aspects of the network performance, which must be deal with. Besides, most protocols developed for specific scenarios may have poorly performance in different ones.

The adoption of a fuzzy-based approach raises important differentials to our work. First, it brings the description of input parameters close to the vocabulary of application developers, relaxing the need of precisely defining values which are not precise in their nature. Furthermore, terms used to refer to both QoS requirements and protocols performance ("long lifetime", "small data loss") have a fuzzy component; thus fuzzy representation gives a more realistic mapping between them. Second, the use of fuzzy rules facilitates the incorporation of knowledge derived from experts and from works performed in field or simulations.

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