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An Evidential Approach for Area Coverage in Mobile Wireless Sensor Networks

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ABSTRACT

The study of coverage problem in uncertain WSN environment requires to consider this uncertainty by taking the best possible decisions, since it is impossible to explicitly represent all the combinatorics to produce a conditional active/passive state nodes' planning in the area of interest, and allow reasoning on various environmental states of the partially known physical world. This paper addresses the problem of area coverage based on the Dempster-Shafer theory. We aim to ensure the full area coverage while using a subset of connected nodes, with minimal costs using a minimal number of dominant nodes regardless of the type of used deployment (random or deterministic). This is ensured by activating a single node in each subset of each geographic sub-area, thus extending the lifetime of the wireless sensor network to its maximum. The comparison of the proposed model denoted Evidential Approach for Area Coverage (EAAC) with two well-known protocols and with a recent one showed a better performance and a slight improvement in the covered area.

Keywords: Mobile Wireless Sensor Network, Area Coverage, Uncertain Theories, Clustering, Connectivity, EfficientEnergy

INTRODUCTION

The last decade has witnessed a growing interest of environment monitoring applications in Wireless Sensor Networks (WSNs) due to their unique potential in the remote detection and prevention of disasters. However, such a critical mission requires a high efficiency to ensure data availability and timely delivery within a reasonable cost. Thus, the deployed WSNs' connectivity and lifetime along with fault-tolerance and cost effectiveness are key network properties. Due to the dynamic physical environment and possible hardware failures, the raw data collected by the sensor nodes are inherently inaccurate and imprecise. The sensor networks in various fields, for various applications, have attracted the interest of researchers in most fundamental problems. Despite the advanced progress in the field of construction technology (MEMS), Sensor networks suffer from many problems. Among them, we can cite technological problems (limitation of monitoring and communication radii, very limited energy reserve, fragile structure), usage problems (non-deterministic protocols, a polynomial or exponential algorithmic complexity, theoretical protocols that are not feasible and not applicable in reality, random deployments), and many other problems. This leads to unbalanced dispersion, incomplete coverage of the area to be penetrated or controlled, rapid loss of data communication, rapid network depletion, etc. Our recent literature overview in the field of sensor networks has shown that the most fundamental problem in wireless sensor networks stills the energy coverage problem efficiency as stated (Cardei and Wu, 2005; Vijayarani and Ramya, 2016). The real world is uncertain, characterized by: (a) the incompleteness of the knowledge of the real state of the world (if the nodes in sub-zone A are completely, partially or not active?), (b) its inaccuracy (the exact positions of the nodes in surveillance? the position of targets and intruders in the area of interest?), (c) the actions' results (the targets are moving, the active nodes are crushed, lost or exhausted), etc. By uncertainty, we mean the hostility of the environment where the sensor nodes are deployed. This could be caused by the variations of atmospheric circumstances, the modifications of the deployed sensor network topologies, the unreliability of the communication radio, etc. All these uncertain causes affect the quality of service and decision on real world information. The atmospheric changes, that impact the physical environment, influence on the position accuracy, the communication power and the sensor nodes' monitoring area in the network. This reality forces us to consider such type of uncertainty. In order to do this, our proposal consists in introducing the fuzziness in the process of scheduling sensor nodes in WSN for several purposes. Among the types of considered uncertainty in WSN, there are:

- Uncertainty in radio communication links: the communication power increases if the Euclidean distance increases. In case of a 3D deployment in mobile environment, energy power and connectivity are constraints that prevent the communication of the sensor nodes within the network.
- Uncertainty in the detection links: environmental interference, angle, nonlinear distance, noise, sensor types, and other factors may introduce uncertainty in the detection process in sensor networks.
- Detection uncertainty in the data collection: when sensors are deployed in hostile environments, different things can affect the collected or detected data quality, such as node sensibility due to signal interferences caused by environment objects (e.g. foliage) or atmospheric phenomena (e.g. cloud), node physical state due to possible deterioration (wind, soil state, animals, etc.).

The coverage problem study in uncertain WSN environments requires to consider the uncertainty by taking the better possible decisions, since it is impossible to explicitly represent all the combinatorics in order to produce a conditional active / passive state planning of nodes in the area of interest, and allow reasoning on the various environmental states of the partially known physical world. This paper addresses the problem of area coverage based on the Dempster-Shafer theory. We aim to ensure the whole area coverage, while using a subset of connected nodes, with minimal costs using minimal number of dominant nodes regardless of the type of used deployment (random or deterministic). The objective is to extend as

much as possible the wireless sensor network lifetime in order to deal with the previous uncertainties and to guarantee the quality of service.

This paper is structured as follows; Section II shows related works on the area coverage. Section III shows the benefits of using an uncertainty model to study the area coverage problem in WSN. Section IV represents a detailed description of our methodology. Section V shows a comparison in two steps: (a) the first one consists in a mathematical demonstration of the proposed technique, (b) the second one consists in comparing our protocol with to simulations; (1) the first one with the protocol TGJD, proposed by Jiang and Dou (2004) and OGCD, proposed by Zhang and Hou (2004), as baseline protocols, and (2) the second one with FPCOA protocol, introduced by Faten and Zaied (2016), using few concrete examples to show the efficiency of our protocol in guaranteeing the area coverage. We finished by a conclusion summarizing the different improvements induced by our protocol in Section VI.

RELATED WORK

One of the most active research fields in wireless sensor network is the area coverage issues. The area coverage is usually interpreted as how well a sensor network will monitor an area of interest? That is to say; how to monitor each point in an area of interest (AoI)? Thus, the area coverage problem is how to monitor all the area of interest using a minimal set of sensor nodes? It can be considered as a Quality of Service (QoS) indicator. Currently, the wireless sensor networks usage is a major interest in various monitoring applications in the area of: environment, battlefields, borders, forests, intelligent spaces, and in the control of industrial and bio-logical disasters. The main objective of using such networks is to monitor with sufficient coverage an area of interest using a small number of sensor nodes during a long period of time (Cardie and Wu, 2004; Huang and Tseng, 2005).

The easiest way to achieve a perfect coverage, especially in area coverage, is to enable all the available sensor nodes at the same time. This activation quickly exhausts the lifetime of the implemented wireless sensor network, that accomplish different tasks, such as control, monitoring and confidentiality during long durations.

Deployment with a high density of sensor nodes on the area of interest produces interferences and overlaps between the communication and monitoring radii of adjacent (neighboring) sensor nodes in the network. Ensuring the coverage, saving the energy, and thus extending the network life by maintaining a minimum subset of active nodes in a dense network, while letting the rest of the nodes in standby mode, has been proven in the literature to be NP-Hard for homogeneous and heterogeneous 2D terrestrial and 3D sensor networks. The area coverage is a non-trivial problem in Wireless Sensors Networks (Kumar et al, 2000; Gupta et al., 2003).

Guaranteeing the perfect coverage leads to guarantee the connectivity of the AoI. Area coverage is difficult to control, to measure and to guarantee using a minimal number of sensors nodes deployed on AoI. Therefore, the area coverage is an optimization problem. Deployment is one of the proposed answers to solve this problem. On one hand, deterministic deployment is preferred in areas where human intervention is possible to replace sensor nodes or to change their batteries. On the other hand, random deployment is necessary in the fields that represent a danger for the human beings or where the intervention is impossible. The treatment of the deployment-based coverage problem is extensively addressed using different strategy domains, such as using: the scheduling process between the Active / Passive nodes' states in the network in (Zaied and Ben Amar, 2003), using the geometric angles and distances between the nodes in (Aurenhammer, 2001), using the disjoint dominating sets and grid strategies in (Shen and Sun, 2006), using the Voronoï diagram and the Delaunay triangulation in

(Aurenhammer, 2001), using the heuristics in (Zaied and Ben Amar, 2003), and many others existing technics.

Deployment with a high density of sensor nodes implies to not necessarily activate all the sensor nodes of the network at the same time, since this creates collisions at MAC (Medium Access control) layer. To maintain the coverage and increase the lifetime of the network, it is necessary to apply a process called "scheduling". The best scheduling is to activate a minimum set of sensor nodes every time and let the rest on standby (off state) until the network will be completely exhausted (Chen et al., 2001). This scheduling process is defined by how long each node is still active and which one is active at the next quantum of time. Scheduling, as defined in (Pinedo, 2005), is a decision making process that is used on a regular basis in optimization and planning services, which is considered as an old method that was used, to activate a set of nodes to control, to guarantee the coverage and the connectivity, and to minimize the energy consumption in the network. Centralized algorithms consider the coverage problem as an optimization problem.

In this context, Alduraibi and Younis (2016) consider the coverage as an optimization problem, where they address the problem with the deployment of a smallest set of nodes to maximize the coverage. The authors propose three optimization models. The first one aims to minimize the sensor nodes number deployed into the area of interest to reach the high reliability level detection. The second model is based on the determination of available nodes' position with nodes number constraint to reach the perfect coverage. The third optimization model aims to minimize the nodes' number deployed in some locations that require low coverage and adjust the deployed nodes' number in other locations that require higher coverage. Liao et al. (2011) present the Glowworm Swarm Optimization (GSO) protocol, which is a new system process based on random deployment to improve the nodes' coverage. GSO considers each node as a single glowworms transmitter and a luminant substance like "luciferin". The luciferin force considered as the link between the transmitter node and its neighboring sensors. A sensor node moves to the low-density area if necessary. A coverage maximization was achieved when a sensor node can move to the low-density area. The disadvantage of GSO is that the nodes must provide a mobilizer and a GPS position detection system, which quickly depletes the network. Guo and Zhao (2012) divide the area of interest into grid and the selected sensor node in the next round is the one situated in the best case. The goal behind this method is to select a smallest set of nodes to guarantee the target coverage and determine the precise positions for the deployed sensor nodes in the network. This method is not efficient in the area coverage and in the wide area where the monitoring of each point is necessary. Alam and Haas (2014) address the problem (coverage and connectivity) of the 3D networks, especially submarine networks, while assuming random and uncontrollable node locations. They have proposed an approach to achieve this objective in distributed and scalable way by partitioning the 3D area into virtual regions or cells, and to maintain an active node in each cell. They show by simulating their approach that the results indicate that the use of cells created by truncated octahedral tessellation of the 3D volume minimizes the number of active nodes. This scheme is fully distributed, and is therefore scales well. Heterogeneity of the radius of each cell can provide efficient k -coverage and k -connectivity, where each point within a network must be within the detection range of k different sensor nodes. Analysis of the results for these schemes for both 2D and 3D networks and the performances' comparison indicate that the performance of the 3D system improves significantly compared to the 2D system for k active nodes.

Other works have used linear programming to solve this problem, as in the works of Berman et al. (2004), Chen et al. (2001), Dhawan et al. (2006) and Meguerdichian and Potkonjak (2003). Heuristic methods were used in (Slijepcevic and Potkonjak, 2001). Chen et al. (2001) and Slijepcevic and Potkonjak (2001) use disjoint sets as a scheduling method to find the number of minimum sets to activate in order to ensure the target's coverage. This scheduling is based on the mixture of Integer Linear Program. In addition, Slijepcevic and Potkonjak (2001) prove that Disjoint Set Covers (DSC) problem is a NP-complete problem. A Various Strategies Proposals in the Literature for (Coverage, Connectivity and

Lifetime) are illustrated in Table 1. The fundamental problem is the coverage in wireless sensor networks, taking into consideration the types of uncertainty that are induced by the communication technology and the detection of wireless sensor network. Quantifying data uncertainty will provide better results and decision making in wireless sensor network applications. Most of existing techniques use heuristics to deal with uncertainty in sensor networks. Uncertainty is impacting all types of coverage works in WSN (area coverage, target coverage and barrier coverage). The uncertainty is coming principally from: the position, the speed, the energy reserve, the reliability and the monitoring range of the sensor node in the network, etc. Deployment is one of the first solutions proposed to guarantee scheduling and coverage. Solution deployment is widely used for area coverage. As an example, Wang and Tseng (2008) consider minimizing the number of sensors and their total movements. The authors solve the problem of deploying sensor to achieve K-coverage of the AoI. They consider two sub-problems: (a) a K-coverage placement problem; and (b) a distribution problem. The placement problem aims to find a minimum number of required sensors and scheduling their location in AoI in order to ensure the perfect coverage by K sensor nodes and to preserve the connectivity in the network. In particular, the distribution problem targets to program mobile sensors to move to designated locations to minimize the power consumption. Liu (2012) proposes a scheduling mechanism based on time-sharing under a quantum of time and activates the sensor nodes within each quantum. Shi and Chen (2015) propose a probabilistic-based dynamic non-deterministic-K-coverage protocol, denoted Optimal Cooperation Scheduling Algorithm (OCSA). This protocol's type is Probabilistic K-coverage and it considers that the target movement is uncertain (either the position or the speed). It follows the Gaussian law. Nevertheless, in most of sensor networks applications, least distance measurement is uncertain due to errors' measurement, measure device reliability, angle's measurement, etc. Handling uncertainty in the study of coverage in sensor networks leads to the difficulty of ensuring the reliability, the robustness, and the optimality of the proposed protocols and algorithms. Recent proposed strategies for coverage, connectivity and energy-Efficiency overview are illustrated in Table 1.

Table 1. A VARIOUS STRATEGIES PROPOSALS IN THE LITERATURE FOR (COVERAGE, CONNECTIVITY, LIFETIME)

Ref. No. Pub. Year	Paper Highlight	Algorithm Proposed/Used	Distributed/ Centralized	Main Issues Handled	Main Drawbacks
Mahboubi (2017)	Potential Field Approach	Clustering, Virtual Force & Merging	Distributed & Centralized	Coverage, Sensor Movement	Obstacle Adaptability, Connectivity
Xie et al. (2019)	Virtual Force	Floor based Scheme	Distributed	Coverage, Sensor Movement, Connectivity	Computational Overhead
Sun et al. (2020)	Optimization Problem	-	Centralized	Power Consumption, Fault Tolerance	Coverage and Connectivity
Shu et al. (2019)	Intelligent Mobile Sensor	Voronoi Diagram	Distributed	Energy Efficiency, Sensor Movement	Obstacle Adaptability
Nasri and Val (2019)	Incremental Deployment	-	Distributed	Coverage	NA
Etancelin and Fabbri (2018)	Electrostatic Problem	-	NA	Connectivity	NA
Tosun et al. (2020)	Mobility for Improving Coverage	-	Distributed	Coverage	NA
Yu et al. (2019)	Virtual Force	Hangerian, SMART, Extended SMART	Centralized	Coverage, Sensor Movement	Obstacle Adaptability
Zhao et al. (2020)	Non Uniform Sensor Distribution	MAND	Centralized	Energy Efficiency	Coverage
Mahjri et al. (2016)	Node Discovery	Machine Learning	Distributed	NA	Coverage
Xiao et al. (2020)	Dynamic Coverage	-	Distributed	Coverage	NA

INTUITION, OBJECTIVES AND ADVANTAGES OF AN UNCERTAIN MODEL FOR COVERAGE IN UNCERTAIN WSN

This section presents the benefits of using an uncertainty model to study the area coverage problem in WSN. These benefits are summarized below:

The intuition behind the use of Dempster-Shafer theory: The active nodes' selection in traditional methods is based on a single criterion, namely the Euclidean distance, the energy reserve, the distance from the center of the cluster, the direction angle, the communication radius or surveillance radius in heterogeneous sensor networks, etc. This selection leads to the network's exhausting and the losing of the coverage and the connectivity in the network. As a result, it induces the failing of the assigned task behind the use of the sensor network. To do this, the combination of several criteria leads to balancing the energy consumption in the network. As a result, it allows to preserve the connectivity, the coverage and increase the network life. Therefore, the use of such uncertainty theory (Dempster-Shafer theory) is advised, especially, in an uncertain environment.

- **The objective behind the use of Dempster-Shafer theory:** Our objective is to define a high-performance strategy to maintain perfect coverage of the area of interest in an uncertain environment (uncertainty in the information that are collected, transmitted, controlled, etc.) with uncertain tools (uncertainty in the range of communication, monitoring, processing, etc.). In one hand, the Dempster-Shafer theory is useful in the imprecise and uncertain data treatment. On the other hand, one or more experts in the field, in general, do the initiation step of mass functions. In our strategy, the initiation of mass functions is done by assigning membership functions (fuzzy logic).

The Dempster-Shafer theory offers an efficient framework for the combination of multi-source information in case of uncertainty. The decision of an active node is made by the use of pignistic probability, and sometimes the measure of belief or plausibility. Other uncertainty theories are useful for other types of uncertainty, such as imperfection, absence, ambiguity, incompleteness, vagueness, etc.

- **The advantages behind the use of Dempster-Shafer theory:** Among the advantages of using such a theory in addressing the coverage problem, we can cite the following ones:

- The uncertainty consideration in the coverage study in a sensor network gives better results for quality of service, coverage quality, energy consumption, etc.
- Atmospheric circumstances affect the performance of the sensor nodes. As a result, non-accurate information measurements are obtained.
- Relying on different criteria, as many as possible, brings the active nodes decision to the perfection and leads to the well nodes' usage in terms of energy and coverage.
- Making the activation decision based on one of the probability measures (Pignistic, plausibility, belief, confidence interval, etc.) gives a high collected information Credibility in the network.

THE PROPOSED STRATEGY DESCRIPTION

In this paper, we assume that the coverage in the area of interest is preserved. i.e.: the deployment of sufficient distributed sensor nodes over the whole area with a high number to guarantee the coverage. The objective is to try to keep a minimum of separate sets with activated nodes among all of them using mathematical techniques, i.e. geometry and computation. We suppose that:

- Each node has two communication radii (minimum RC_{min} and maximum radius RC_{max}) and two monitoring radii (minimum RS_{min} and maximum surveillance radius RS_{max}). Each node can configure,

as needed, its communication radius between the minimal and maximal values, as well as for the monitoring radius (Figure 1.).

- Used nodes have the same characteristics (all nodes are homogeneous), such as memory power, processing power, energy reserve, and even communication and monitoring power.
- The deployment of sensor nodes is done in a random way with a high density in the area of interest. Therefore, the number of nodes is sufficient enough to guarantee the traditional coverage. That is to say, the coverage is initially ensured.
- The base station (BS) is able to know the positions of the sensor nodes by a localization tool, like a GPS (Global Position System) and it does not suffer from constraints such as power supply, calculation and storage.

In this paper, according to our context, which consists on the cover against intrusion, we propose to use a combination between the theory of fuzzy logic and the theory of evidence, this could be justified by:

- The fuzzy set theory allows representing information values with its imprecision.
- Defuzzification allows transforming fuzzy sets in crisp values useful for decision making.
- The evidence theory proposes an efficient framework for multi-source information combination under uncertainty.
- The decision making process can use the Pignistic probability, and sometimes the measure of belief or plausibility.

Using this compromise, our objective aims to define a method to achieve a perfect coverage that considers information uncertainty. Our intention is to improve the final decision of the intrusion discovery and cover the noncovered subareas.

The steps of proposed approach

The proposed protocol is divided into three steps: (a) the pre-configuration step, (b) the deployment step which is constructed by i) the initial deployment stage, and ii) position adjustment step, and (iii) the coverage step. The area of interest is a geographical one (AoI), and to apply and benefit from our protocol, and benefit from the integration of the uncertain deployment of sensor nodes to ensure the perfect coverage of area of interest (AoI). Then, it consists in (a) configuring the sensor nodes of such a spell as each node provided by configuration parameters in its memory: the position, a unique node identifier, and a unique identifier of the set (the set of node that will work in collaboration performed at the Base Station (BS) as a prerequisite after the initial deployment.

The Pre-Configuration step: Each sensor node must contain in its memory the four positions of the square zone on which they are deployed $P_1(x_1, y_1, z_1)$, $P_2(x_2, y_2, z_2)$, $P_3(x_3, y_3, z_3)$ and $P_4(x_4, y_4, z_4)$, the cluster number $Num - set$. In this way, the square diameter D constructed by these four points (P_1, P_2, P_3, P_4) does not exceed the measure of monitoring measurement radius R_s . This means:

$$D = \frac{\sqrt{2}}{2R_s} \quad (1)$$

The justification of this choice is stated in the simulation section.

The deployment step: The deployment step consists of two stages:

The initial deployment stage

Nodes are randomly deployed to previously specified geographic subareas (before initial deployment), and the initial deployment must be by subarea at a time.

The position adjustment step (Clusters construction)

Each sensor node is endowed by a mobilizer, which will be used once to straighten the initial deployment. Each node compares its position with the four given positions P_1 ; P_2 ; P_3 and P_4 . If the position is outside of the square, then the mobilizer moves the node to the square zone. The area subdivision under subareas is based on the Euclidean distance criterion, where the distance between them does not exceed D .

this allows the nodes to be grouped together. Hence, the sets of nodes in each subset area represented by clusters of nodes, as it is illustrated in *Figure 2*.

The coverage step (The coverage process)

Our process uses the concept of groups and group leaders for collaborative tasks (selection of leaders and chief-chiefs-groups) through the evidence theory. This step considers that all the physical environment and nodes information are uncertain. In order to give credibility to the evidence theory, we will use fuzzy logic as a mass function automation paradigm. This operation has been done manually by domain experts (candidate selection and assignment of mass functions). The sensor nodes are considered as sources of uncertain information, such as the position, the radii of communication, the rays of monitoring, and the energy reserve as uncertain criteria. The coverage process is composed of the following Dempster-Shafer theory's tasks: (a) selection of the discernment frame for each cluster, (b) initiation of mass functions for these candidates (to be Head Cluster or Head-Head-Cluster), (c) combination of candidates, and (d) decision making. We have defined a mass function initiation model based on fuzzy logic through two operations:

The selection of Cluster-Head

- After the position adjustment step, by which the nodes are grouped under clusters, nodes that are closer to the center of each sub-zone, and with a larger energy reserve are selected as potential candidates as sub-zone heads. According to relation (2), any node can cover the geographical sub-area in which it has been deployed (*Figure 9.a, Figure 9.b*) (the mathematical demonstration of the choice is detailed in the simulation part).
- The CH node choice is uncertain as depicted by (*Figure 3*): if there are more than one node, which have the same Euclidean distance to the Cluster center, then the choice will be done based on the combination of the Euclidean distance with the center and the energy level using the TDS theorem. That is to say, the Cluster-Head is chosen as the node with the highest mass based on these two criteria.
- After each communication cycle, the Cluster-Head selection step is repeated until the energy level of all the nodes of a cluster reaches zero, hence the coverage rate of the zone will be reduced.

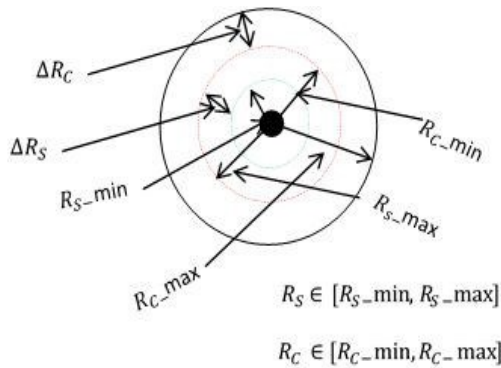


Figure 1. Uncertain Sensing and communication ranges (R_S, R_C).

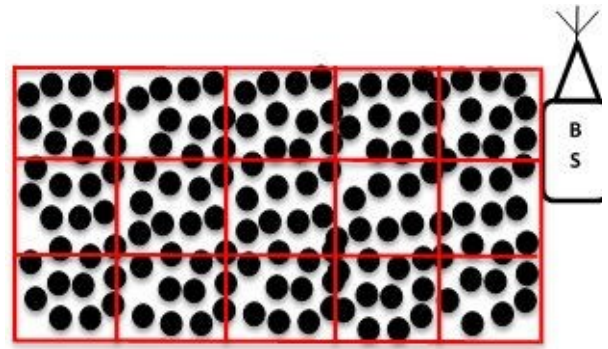


Figure 2. One cluster of nodes by a single subarea.

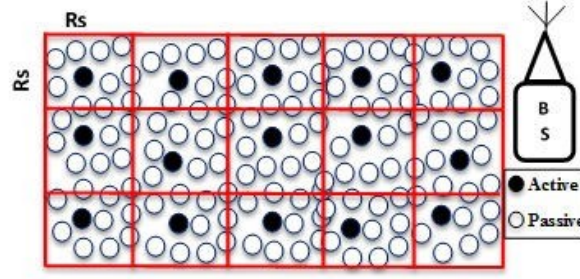


Figure 3. The Cluster-Head of each subarea.

The proposed model to initialize mass functions

The present approach aims to find an optimal solution to solve the discovery problems by proposing a new scheduling strategy of the states (active / passive) of each sensor node, based on the uncertainty theories, namely the Evidence and the Fuzzy Set Theories. This strategy aims to develop an activation / deactivation strategy of the sensor nodes to cover the area of interest with a minimal set of sensor nodes. Our approach is based on the overlap between fuzzy logic and evidence theory to initialize mass functions and to make a relevant decision (Figure 4).

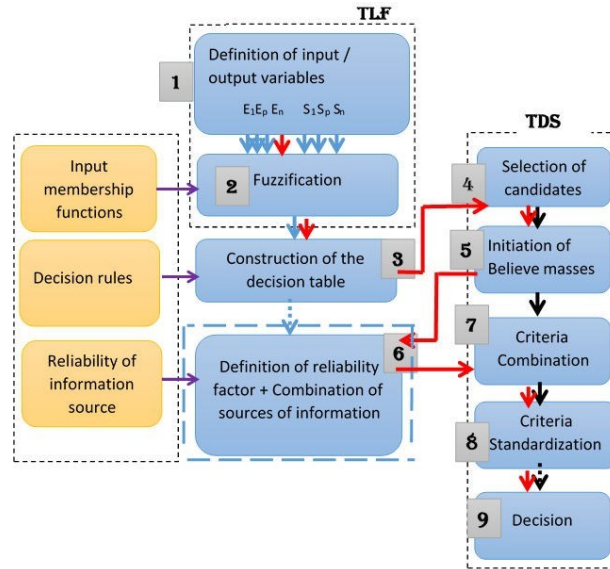


Figure 4. Pipeline of the approach using a compromise of Evidence Theory and Fuzzy Set Theory.

The approach is a succession of the following steps:

Step 1: Definition of the input variables (E_1, E_2, \dots, E_n) of different used source information, and the output variables (S_1, S_2, \dots, S_n).

In this step, the needed fuzzy subsets for each fuzzy variable, their type, and their abbreviation must be defined. Each pairing criterion linked by a class (geometry class, semantic class, topological class, toponymical class, etc.). The criteria for area coverage are each tied by a fuzzy variable, and a fuzzy subset.

Example: we took two input variables, and one output variable.

- The fuzzy variable: Euclidean Distance (D^e), its type (Input (E)), D^e

- $\in \{Near(P), Middle(M), Far(L)\}$.
- The fuzzy variable Energy Reserve (R^e), its type (Input (E)), $R^e \in \{Near(P), Medium(M), Far(L)\}$.
- **Step 2:** Fuzzification, which consists of the fuzzy qualification of the fuzzy values of a variable, that is to say, to determine the inputs and outputs values necessary and / or sufficient for modeling (the fuzzy representation of the variables blurred according to fuzzy subsets). In this step, the interval (min value and Max value) is defined according to the context, and the information's sources taken for the scheduling operation.

Example: For or the already defined variables, we choose::

- Near(N) $\in [0 : 30]$, Middle(M) $\in [0 : 60]$, Far(F) $\in [30 : 150]$.
- Deplete(P) $\in [0 : 0.30]$, Middle(M) $\in [0 : 0.60]$, Full(L) $\in [30 : 1.50]$.

We choose the following criteria: Euclidean distance and the energy reserve.

Step 3: Construction of the decision tables according to an expert in the uncertain information system and WSN domains (see *Figure 5* and *6*). We have added a step to define the possible decisions (Active, Undecided, Passive), according to the distance.

D^e	N	M	F
N	A	A	U
M	A	U	P
F	U	P	P

Figure 5. Decision Table for Distance Variable.

R^e	D	M	F
D	A	A	U
M	A	U	P
F	U	P	P

Figure 6. Decision Table for Energetic Reserve Variable.

Step 4: The selection of the candidates and the definition of the frame of discernment is done, after the definition of the thresholds based on the fuzzy subsets.

After the defuzzification of the fuzzy subsets built during the previous steps, one can select candidates and define the framework of discernment. That is to say, one can define all the possible solutions of the problem of nodes' activation for coverage in the network. First, we select the neighboring nodes that can be active, and then we define the experimental threshold used for the selection of potential candidates according to the Euclidean distance and the energy reserve. Then, we can see which are the nodes' candidates that can be activated to guarantee the coverage of AoI according to the definition of a set of rules:

Step 5:

Initialization of the belief's masses from the fuzzy values. This step allows specifying automatically a method to initialize the masses functions. First, all the neighboring sensor nodes are considered as candidate nodes. We define an experimental threshold to choose potential candidates according to the Euclidean distance and the energy reserve. We get a set of nodes that are considered as potential candidates. The initialization of the basis of mass belief requires an expert. In this work, we tried to give a method to facilitate it.

- The strategy of Initialization of mass functions
 - The initiation of mass functions involves using fuzzy information sources, i.e. the Euclidean distance, and the energy reserve. The followed methodology consists on representing each source of information by a

fuzzy graph, as shown in the following *Figure 7*. The computation is done according to the definition of a set of rules:

- Calculation of the degree of membership for each part:

$$\mu^i = \max(\mu_1^i, \mu_2^i) \quad (2)$$

Where, μ_1^i, μ_2^i represent respectively the membership coordinates of the fuzzy graph of the abscissa x in each part i , as shown in *Figure 7*.

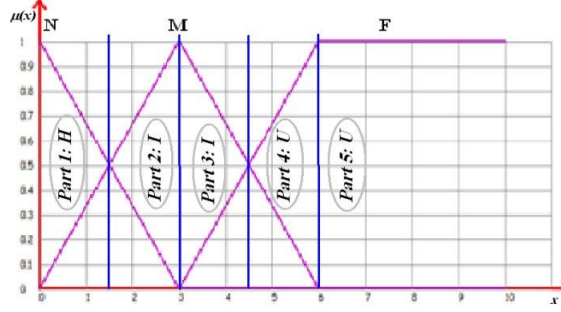


Figure 7. Distance partition into fuzzy sets.

The protocol unroll

- Initially the protocol is centralized, the base station constructs the sub-zones and sends them to each set of nodes as a sequential number that remains the same for each node. Each node sends a probe message to their neighbors containing the set number, the geographical position and the energy level.
- Each node within the same set, which receives the message, starts to construct their neighborhood table containing the parameters: (*Num* – *Cluster*, *Position*(x, y, z) and *EnergeticLevel*).
- Each node combines the parameters of their neighborhood table to find out which Cluster-Head could be chosen for this communication cycle by the application of the Dempster-Shaffer operator. Mass functions are defined as:

The source of Euclidean distance information

If a node u belongs to the cluster i is located at a distance d from the center of the cluster with the diameter of the cluster is R_i , then:

$$m_{Euc}(u) = (1 - d)/R \quad (3)$$

The information source of the energy level

If a node u belongs to the cluster i with an initial energy reserve E_0 and a current energy reserve, so:

$$m_{Eng}(u) = (1 - E)/E_0 \quad (4)$$

The information source of the sensing range

If a node u belongs to the cluster i varies its sensing range to R_S , ($R_S \in [R_{S_min}, R_{S_max}]$), then:

$$m_{R_S}(u) = (1 - R_S)/R_{S_max} \quad (5)$$

The information source of the communication range

If a node u belongs to the cluster i varies its communication range to R_C , ($R_C \in [R_{C_min}, R_{C_max}]$), then:

$$m_{R_C}(u) = (1 - R_C)/R_{C_max} \quad (6)$$

The combination

The combination of the masses of these four sources according to Dempster-Shaffer operator gives:

$$m_{Euc} \oplus m_{Eng} \oplus m_{R_S}(u) \oplus m_{R_C}(u)(A) = \begin{cases} 0 & \text{if } A = \emptyset \\ \frac{1}{1-\lambda_c} \sum_A m_{Euc}(A) \times m_{Eng}(A) \times m_{R_S}(A) \times m_{R_C}(A) & \text{if } A \neq \emptyset \end{cases} \quad (7)$$

The selection of Cluster-Head

The node with the highest mass function will be chosen as the Cluster-Head for the current communication cycle. Each CH could vary its radii (R_S, R_C) to maintain connectivity between nodes of the neighboring clusters and ensure coverage of uncovered portions.

The selection of a new Cluster-Heads

At the end of each communication cycle, the nodes of each cluster consult their neighborhood tables and combine their parameters and choose their new Cluster-Heads.

SIMULATION

Firstly, our simulation is based on an optimization step, in which, we mathematically demonstrated the efficiency of our approach (EAAC) in guaranteeing a perfect coverage of an AoI. Then, in the second part, a comparison is proposed with two basic protocols, namely OGDC in (Jiang and Dou, 2004) and TGJD in (Zhang and Hou, 2004), and with one more recent protocol, which uses the position adjustment, denoted FPCOA in (Faten and Zaied, 2016), using two case studies. In the third use case of the simulation, we varied the ranges of the monitoring radius and recorded the results of coverage ratios, connectivity and Energy consumption.

Table 2. COMPARISON OF USED PROTOCOLS

Protocol	Connectivity				Coverage	Deployment		Took the uncertain
	$R_s = R_c$	$R_s \leq R_c$	$2R_s < R_c$	$2R_s = R_c$		Large scale	Adjustment position	
OGCD	Yes	Yes	Yes	Yes	Yes	No	No	No
TGJD	yes	Yes	Yes	Yes	No	No	No	No
FPCOA	No	No	No	Yes	Yes	No	Yes	No
EAAC	No	No	No	Yes	Yes	Yes	No	Yes

Weaknesses/Strength of Optimal Geographical Density Control OGCD, TGJD, FPCOA and EAAC protocols

The advantages and limits of the protocols OGCD, TJGD, FPCOA and EAAC protocols in terms of connectivity and coverage are presented in Table 2.

OGCD is oriented connectivity and coverage in large scale geographic areas. Despite its appearance in 2004, it uses high density deployment as a strategy to ensure connectivity and provide coverage. The protocol TGJD of Tian, Georganas, Jiang and Dou studies the possibility of guaranteeing connectivity

in all possible cases; ($R_S = R_C, R_S \leq R_C, R_C < 2R_S, 2R_S = R_C$). For this reason, we find that it is interesting for us to benefit from these advantages in our strategy. FPCOA protocol addresses the sensor placement problem for WSN. Then, it focuses on zone coverage based on the deployment strategy. This protocol achieved the optimal adjustment of the placement of the nodes in the network, and it achieves a dual purposes: the maximization of coverage and connectivity between nodes with neighboring clusters and the coverage guarantee of uncovered portions.

TGJD and OGDC protocols ensure connectivity and coverage in wireless sensor networks until the first node will be exhausted in the network and then the number of dead nodes rapidly increases in some cases where the dispersion of nodes in the network is minimal (i.e. the distances between the nodes is great). Moreover, the depletion of the nodes located in the center allows complete cancelation of the quality of coverage (QoC) and the quality of connectivity (QoN). For this reason, the implementation of a strategy is required to enhance the coverage and the connectivity until the total network depletion. Our strategy aims to divide the network into sub-areas considered as Geographic Clusters and to use only one active node per cluster to monitor and transmit the data. This node is the Cluster-Head. In each cluster, other nodes must remain passive. The CH choice is uncertain using several criteria; such as the Euclidean distance from the Cluster center, the energy reserve, the communication range and the monitoring range. For this reason, the Dempster-Shafer theorem was used. The selection criteria represent singleton mass functions (i.e. there is no intersection between the criteria). To cover the clusters, even after the exhaustion of their nodes, the capacity of increasing the communication and the monitoring radius is necessary. Each node is endowed with R_S and R_C varying between R_{S_min} and R_{S_max} , R_{C_min} and R_{C_max} . Such as $R_{C_min} = R_{S_max}$ as illustrated in *Figure 1* respectively. This variation is random and done after a time period, and after the last neighbor node received the message sent from the active node. The CH choice and the variation of the monitoring and communication capacities are repeated until the total depletion of the network.

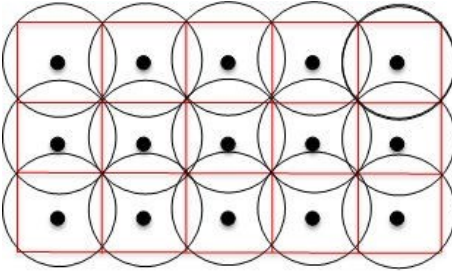


Figure 8. The Central Nodes of the subarea covers the entire zone

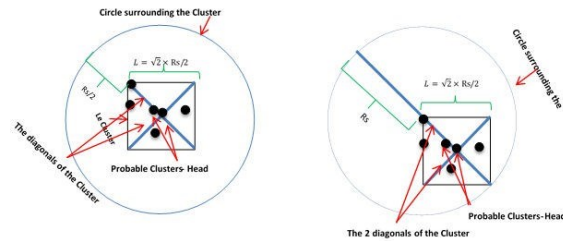


Figure 9. a. The point of intersection of the diameters is the center of the circle surrounding the square cluster (center case), b. The point of intersection of the diameters is the center of the circle that surrounds the square cluster.

Mathematical demonstration of the technique

Mathematically, we considered the sub-zones as squares and we used the concept of cycle that surrounds the square, as shown in *Figure 8*, and *Figure 9*. The latter shows that we can cover an area by a node that is located in the center of the zone. The choice will be made by combining the different parameters (the distance from the center, the energy reserve and the angle with respect to the base station using the Dempster-Shafer theory (TDS). We consider a sub-zone with their nodes as a cluster, which means that each cluster contains a sufficient number of nodes to ensure its coverage. Each node that belongs to a zone must be able to cover it. Even if a node is located in the corner of the zone, it is able to cover it. In order to satisfy these conditions, the length of the square side L must be defined as:

$$L = \frac{\sqrt{2}}{2} \times R_S \quad (8)$$

By applying the Pythagorean Theorem, the nodes located at the 4 corners of the square with a monitoring radius R_S can cover the whole area of the square with diameter R_S , as shown in Figures; (Figure 9.a, Figure 9.b); Therefore, a side L of the square is defined as:

$$L^2 = R_S^2 + R_S^2 \quad (9)$$

Analysis of results

The connectivity between the nodes in the Cluster:

If a node u with a monitoring radius R_S which is located on a corner of a square with a diameter $D = 2 \times R_S$. Then, its circle can surround the node v which is located at a distance D , Then, its circle can surround the node v which is located at a distance (Figure 9.a, Figure 9.b). Indeed, if the nodes u and v are inside the same square, then the distance separating them does not exceed D . As a consequence, u can cover the monitoring zone of any node v , which is located at the distance $D_{u,v} < D$. Therefore, the connectivity is guaranteed.

The duration of coverage and energy consumption

Since the connectivity is maintained for all nodes in each cluster and since our protocol is used to activate a single node u to perform the monitoring of each subarea and the other nodes in the cluster remain passive, the coverage is ensured. Then, if the cluster contains N nodes and each node can still monitoring a time period t before being exhausted, then, the maximum lifetime of a cluster is defined by the following relationship:

$$T_u = t \times N \quad (10)$$

Therefore, the minimum total duration of the wireless sensor network can be defined by the following relation:

$$T_{WSNmin} = \min(N_{n_1}^1, N_{n_2}^2, \dots, N_{n_p}^p) \times t \quad (11)$$

Thus, the network still connected and covered until the exhaustion of the last sensor node in each subarea. Then, the maximum duration of the wireless network array is defined by the following relationship:

$$T_{WSNmax} = \max(N_{n_1}^1, N_{n_2}^2, \dots, N_{n_p}^p) \times t \quad (12)$$

The average network lifetime is:

$$T = (T_{WSNmax} + T_{WSNmin})/2 \quad (13)$$

This duration is the greatest expected one compared to all the already presented coverage protocols.

Comparison between the TGJD, OGDC, FPCOA protocols and our protocol EAAC)

Use-case study 1

For the study of the coverage and the connectivity of our approach and TGJD, OGDC, and FPCOA, we used an example where the coverage is not guaranteed by the application of the TGJD protocol and guaranteed by our protocol EAAC. In this example, since each Cluster (geographic sub-area) has the dimensions (L, W) , such as $(L, W) = \frac{\sqrt{2}}{2} \times R_S, \frac{\sqrt{2}}{2} \times R_S$ is covered by a single node. Then, the coverage is complete. Thus, the connectivity is satisfied (if $R_C \geq 2 \times R_S$), as illustrated by Figure 10. Figure 11 shows that according to the TGJD, OGDC and FPCOA protocols, the node 2 will be activated, then it sends the probing message to nodes 1, 3, 5, 13 and finds that 1 is already active. Then, the node 2 remains passive. This is the case also for nodes 3, 5, 13 since they found the node 4 active. Indeed, the nodes 1 and 4 are neither connected nor covered within the sub-zone surrounding them like, for nodes 17, 19, 20, 29, 27, 37, 39, 38, 43, 47, and 50 (not guaranteeing neither coverage nor connectivity between them).

Consequently, in this use-case, TGJD, OGDC, and FPCOA protocols do not guarantee the coverage nor the connectivity between the sensor nodes. However, our protocol EAAC did, since, each sensor node within each sub-zone can cover the latter and guarantee the connectivity between the nodes of the adjacent sub-areas. We conclude this study by notifying that our protocol maintains the connectivity between the nodes and is considered as the necessary condition for coverage during all communication cycles (throughout the network lifetime). Accordingly, it maintains the coverage and minimizes the energy consumption.

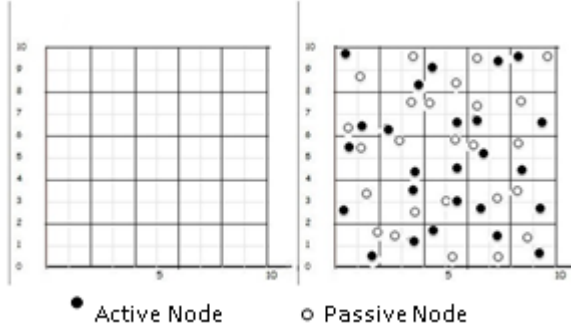


Figure 10. a. The area of interest before deployment, b. The area of interest after deployment (The proposed protocol)

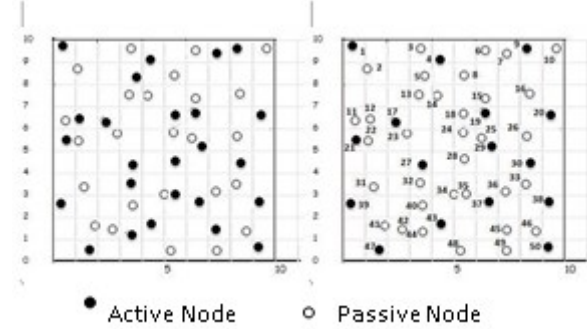


Figure 11. a. The area of interest covered by the application of the TGJD , OGDC, and FPCOA, b. The case where the TGJD, OGDC, and FPCOA does not guarantee the entire coverage, nor the connectivity

Use-case study 2

This studies the connectivity between the sensor nodes, the coverage rate and the energy consumption in the network. The simulations' results present the connectivity, the coverage and the energy consumption as a function of the time. They are depicted in Figure 12, Figure 13 and Figure 14 respectively.

The connectivity rate between the nodes in each Cluster

The connectivity rate between the nodes within each sub-zone (cluster) is guaranteed as depicted by Figure 12. Moreover, this connectivity is guaranteed between the sub-zones even if the nodes of a sub-zone are completely defective. This guarantee starts from 100% and decreased until 80% after 500 iterations and reached 30% at 900 iterations. However, this is not the case for the other protocols. The connectivity is reduced from 100% to 73% and from 100% to 61% for OGCD and TGJD respectively after 500 iterations, and reached 22% and 5% at 900 iterations respectively. Also, we achieved a slight gain in the connectivity compared to FPCOA, as shown in Figure 12.

The coverage rate

Since the connectivity is guaranteed, then the coverage is also guaranteed with a rate of 100% in the first 300 iterations. This decreased to 80% at the 600 iterations and reached 26% after 900 iterations. On the other hand, OGCD and TGJD protocols decreased from 100% to 77% and to 20%, and from 97% to 64% and to 2%, respectively in the same time intervals. Besides, we achieved a slight gain in the coverage compared to the FPCOA protocol, as shown in Figure 13.

The energy consumption

The energy consumption with EAAC is reduced compared to TGJD and OGDC protocols. Figure 14, shows that the energy consumed by our protocol EAAC does not exceed 0.05 unit after the first 300 iterations and does not exceed 0.84 units after 600 iterations and reached 0.32 units after 900 iterations. On the other side, TGJD and TGJD protocols in the same time intervals increased the energy consumed from

0.125 unit to 0.355 unit and finally to 0.500 unit for TGJD, and increased from 0.065 unit to 0.155 unit and finally to 0.345 unit for OGCD. FPCOA protocol minimizes the energy consumption more than these two old protocols, since it manages to minimize the energy consumption to 0.098 unit during the 600 iterations, then quickly increases to 0.335 unit in the 300 iterations that follow. This increase is caused by the depletion of the majority of the sensor nodes in the network.

As a result, using our protocol EAAC improves the energy consumption. Therefore, keeps the coverage and the connectivity for a long time compared to the two old protocols OGDC and TGJD, and even with the recent one FPCOA.

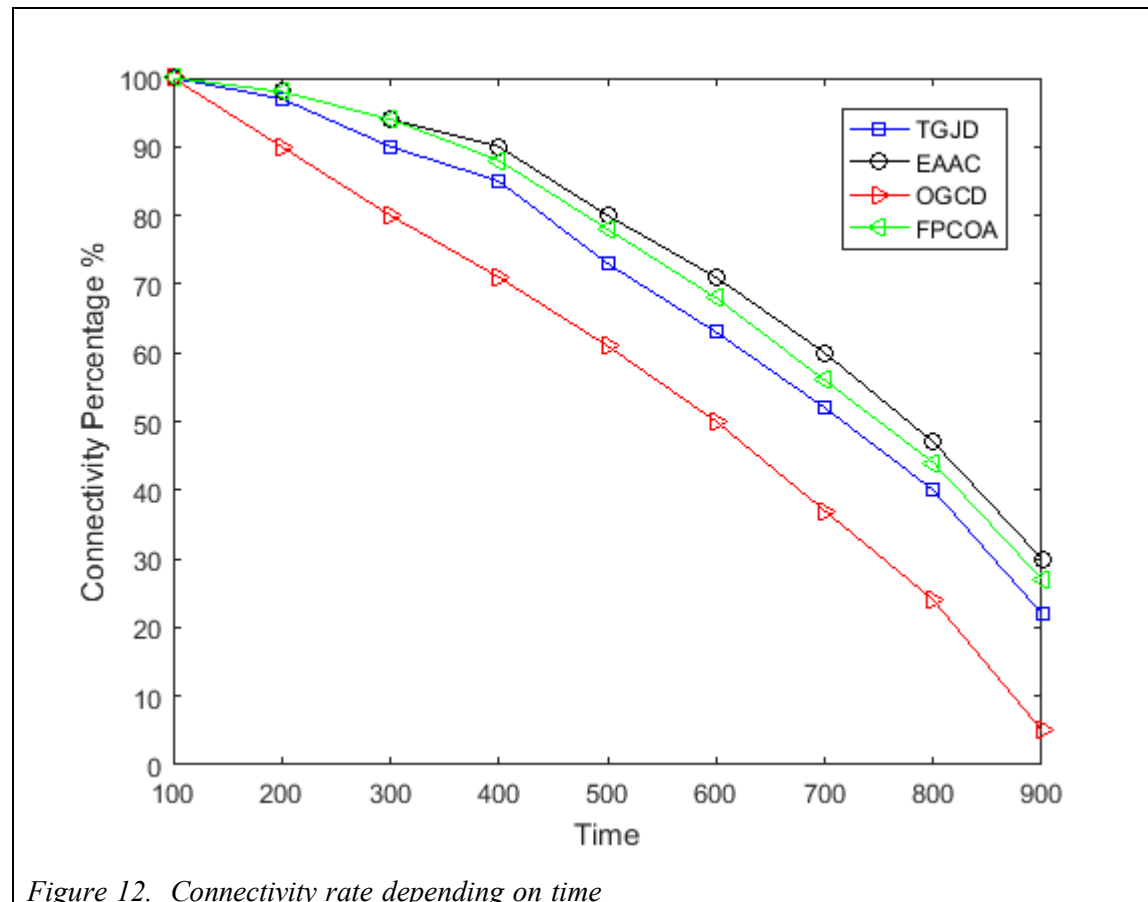


Figure 12. Connectivity rate depending on time

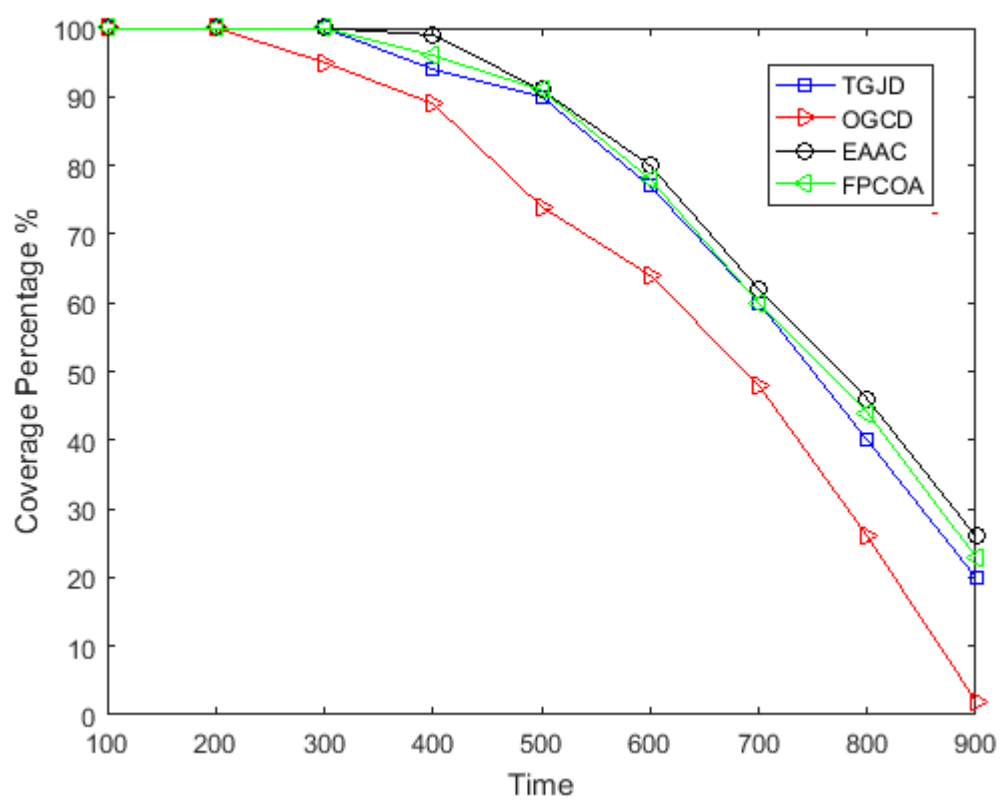


Figure 13. Coverage rate depending on time

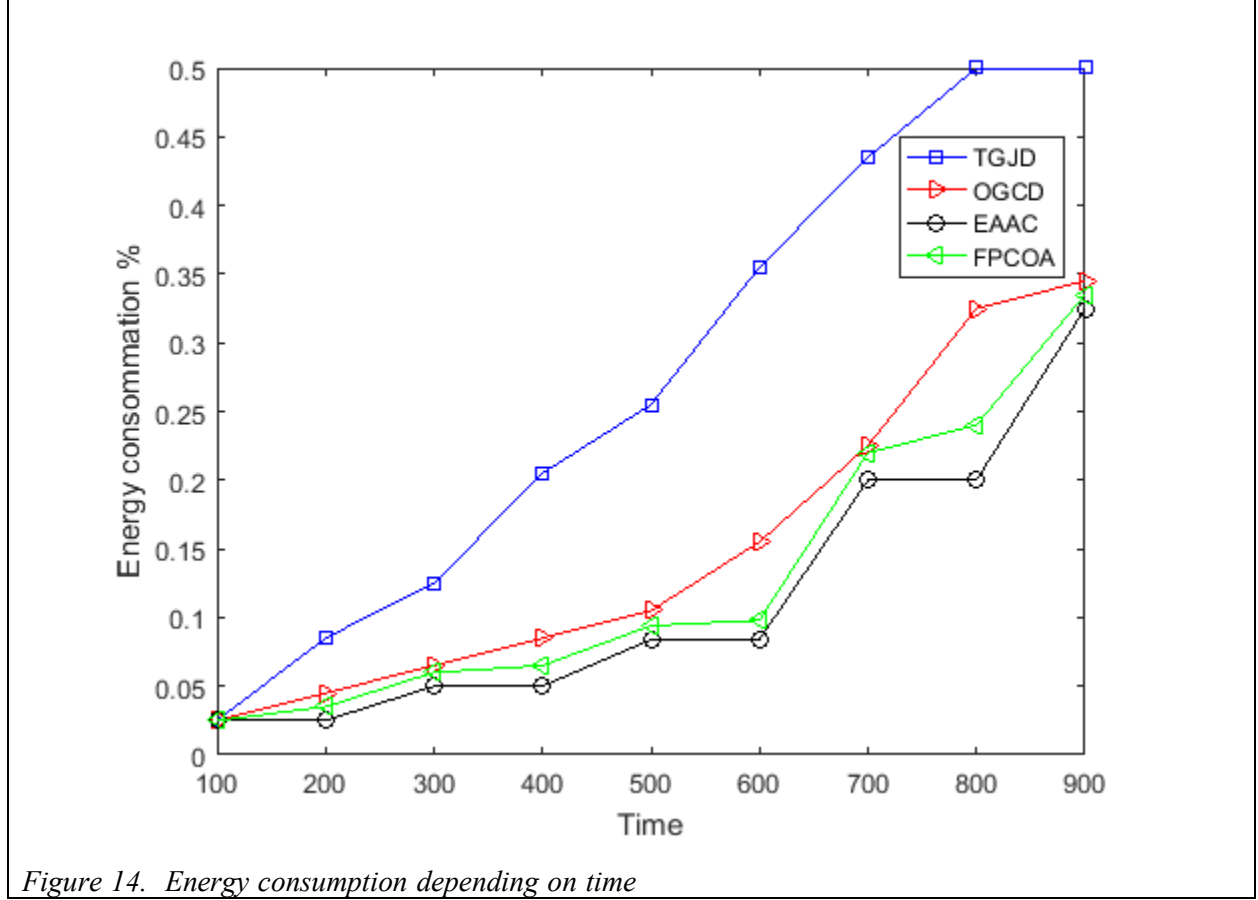


Figure 14. Energy consumption depending on time

Studying the EAAC performances

1) Data Simulation:

In this study, we will vary the monitoring radius and record the results of the coverage ratio, the connectivity ratio and the energy consumption.

Table 3. Simulation data (USE CASE 3)

Configurations	Value
Area of interest (AoI)	100 × 100 meters
Communication range R_c	$\in [5, 20]$ meters
Sensing range R_s	$\in [5, 20]$ meters
Deployed Sensor Nodes Number	10 to 50
Number of repetitions	5 times

To do this, we based our simulation on random deployment assuming that the deployment area is square measuring 100 × 100 m, and we have the communication and monitoring radii ($R_c \in [R_c - min; R_c - max]$ and $R_s \in [R_s - min; R_s - max]$) and deployed the sensor nodes 5 times with 10 to 50 sensor nodes for deployment and according to their communication ranges (R_c) between $R_c - min = 10$ to $R_c - max = 20$ meters and a monitoring ranges (R_s) between $R_s - min = 5$ to $R_s - max = 10$ meters, that satisfies relationship $R_c = 2R_s$, as shown in Table 3.

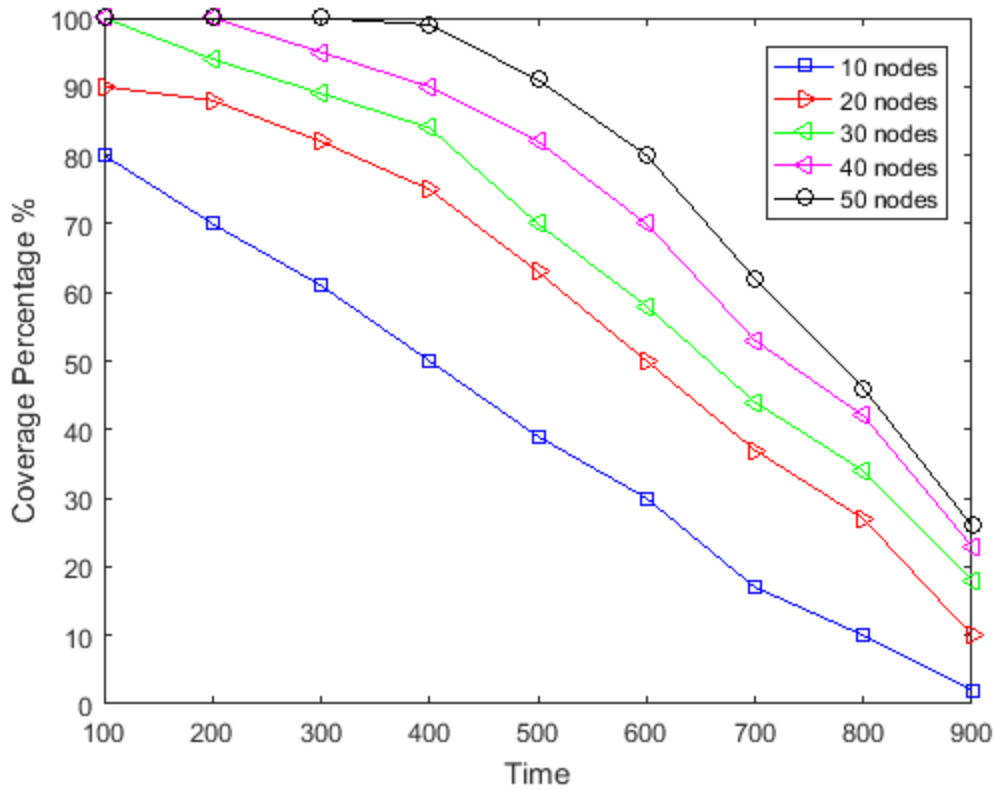


Figure 15. EAAC Comparison of coverage rate according time

2) Results Analysis:

In this simulation, we run the scenario five (5) times, where we varied at each time the number of deployed nodes. The simulation results are shown in the Figure 15. This figure shows that the coverage rate increases with the number of the deployed nodes. This is intuitive since we increase the probability to cover more zones. Besides, using our nodes' activation strategy, we activate only one node per zone, thus we keep the network alive for a longer time, when the number of nodes increases. Therefore, these various EAAC comparisons show the growth of the coverage ratio as a function of the deployed nodes number. This growth shows the advantage of taking uncertainty in the environment and the efficiency of using the Dempster-Shafer theory to deal with the coverage problem in uncertain environments.

CONCLUSION

In this paper, efficient energy coverage issues is investigated in WSN, where it is difficult to deploy and maintain nodes in predetermined positions in an uncertain environment. Therefore, a coverage strategy with a minimum number of connected nodes is required to guarantee a better quality of coverage and quality of service. A novel approach is proposed. The latter is based on Dempster-Shafer theory applied to the node clusters' construction and the Cluster-Head node selection. Finding the right positions and the minimum number of active sensor nodes for perfect coverage, which is one of the most difficult problems in the literature, is our main contribution in this paper. Using simulation and comparisons with the literature, we have shown that taking into consideration that the environment is uncertain and using the Dempster-Shafer theory helps to answer to these questions: "how

to activate nodes in uncertain environment?” and “how many minimum nodes are needed to be activated to guarantee the coverage?”.

We consider that the cluster-head selection is an imprecise operation. In fact, we used the CH for dual roles; as an active sensor node that provides coverage at the cluster level, and as a harvested data transmitter sensor node at the cluster level.

Moreover, Considering the following criteria (the Euclidean distance, the energy reserve, the communication radius and the monitoring radius) as imprecise information sources, we used the Dempster-Shafer theory to combine uncertain criteria and to choose the Cluster-Head node within each cluster, which gives an optimal choice. In future works, we will use other uncertain theories compromise for this objective to study their efficiency.

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