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Sami Mnasri, Adel Thaljaoui, Nejah Nasri, Thierry Val. A genetic algorithm-based approach to optimize the coverage and the localization in the wireless audiosensors networks. IEEE International Symposium on Networks, Computers and Communications (ISNCC 2015), May 2015, Hammamet, Tunisia. pp. 1, 10.1109/ISNCC.2015.7238591 . hal-01387795

HAL Id: hal-01387795

<https://hal.science/hal-01387795>

Submitted on 26 Oct 2016

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The contribution was presented at ISNCC 2015:

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To cite this version : Mnasri, Sami and Thaljaoui, Adel and Nasri, Nejah and Val, Thierry *A genetic algorithm-based approach to optimize the coverage and the localization in the wireless audiosensors networks*. (2015) In: IEEE International Symposium on Networks, Computers and Communications (ISNCC 2015), 13 May 2015 - 15 May 2015 (Hammamet, Tunisia).

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A genetic algorithm-based approach to optimize the coverage and the localization in the wireless audio-sensors networks

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Abstract—Coverage is one of the most important performance metrics for sensor networks that reflects how well a sensor field is monitored. In this paper, we are interested in studying the positioning and placement of sensor nodes in a WSN in order to maximize the coverage area and to optimize the audio localization in wireless sensor networks. First, we introduce the problem of deployment. Then we propose a mathematical formulation and a genetic based approach to solve this problem. Finally, we present the results of experimentations. This paper presents a genetic algorithm which aims at searching for an optimal or near optimal solution to the coverage holes problem. Compared with random deployment as well as existing methods, our genetic algorithm shows significant performance improvement in terms of quality.

Keywords— Target Coverage, Audio Localization, Mobile Node, Deployment; Genetic Algorithm; NSGAI

I. INTRODUCTION

Coverage area can be defined, according to [1], as: "the area in which a sensor can perform its sensing, monitoring, surveillance and detection tasks with a reasonable accuracy (i.e., the sensor reading have at least a threshold level of sensing detection probabilities within the area). The target coverage (called also point coverage) interest in controlling a target in the field of interest that can be stationary or mobile. The k-coverage problem requires preserving at least k sensor nodes controlling any target to consider it covered. The works of [2] present and discuss the types of coverage problems. The localization of the sensors is the most significant factor related to the cover network. Also, localization is an important issue when there is an uncertainty of the exact position of some nodes. Indeed, in wireless sensor networks, the location information is crucial especially when an unusual event occurs. In this case, sensor node that detected that event needs to locate it and then report this position to the base station.

The use of acoustic information captured by sensor nodes is one of the axes that can bring more possibilities in term of

localization. In our work, time difference of arrival (TDoA) using correlation technique was used for estimating the delay between two signals captured by two different microphones placed on one node. The direction of arrival of the sound source can be obtained using this delay and the sound source is positioned by adopting the geometric location method.

For most deployment formulations, the problem of optimal placement of the sensor nodes is proven NP-hard [3]. Consequently, for large scale instances, this problem cannot be solved by deterministic methods such as the circle packing algorithm. We define the problem formally and we propose an efficient genetic algorithm to resolve the problem of the coverage holes after the initial random deployment. For a given number of sensors, the proposed algorithm attempts to maximize the sensor field coverage using a set of operators.

In our works, we are interesting in using WSN in smart buildings applications. Despite the different challenges in WSNs, research works have only focused on post-deployment problems such as: sensors localization, MAC efficiency or routing optimization, etc. Our works aim to ensure the deployment of the nodes while maximizing the coverage and optimizing the audio localization using an efficient genetic algorithm. Our proposed model is different from the existing models since it integrates sensor node deployment, and audio localization approach in a single model.

The rest of the paper is organized as follows: In Section II a mathematical modeling is proposed. In Section III, the genetic algorithm based approach is explained. In Section IV, the target localization issues are discussed. In Section V, numerical results are presented and discussed and finally, Section VI concludes this paper.

II. RELATED WORKS

Different research works deals about the deployment problem in order to maximize the coverage in WSN. The works of [4] and [5] interests in studying the sensor deployment problems. Also, in [6], the coverage problem is studied in the domain of the robot exploration. This work considers each robot as a sensor node and the used algorithm

deploy nodes one by one incrementally. Hence, the proposed algorithm is computationally expensive, when we increase the number of nodes. Some recent researches proposed genetic algorithms to resolve the deployment problem in WSNs. As example, the works of [7] propose a multi-objective paradigm to solve the deployment and power assignment problem. This evolutionary algorithm is based on the MOEA/D (Multi Objective Evolutionary Algorithm/Decomposition). They gave a comparison between the MOEA/D algorithm and the NSGAI algorithm. The former is better in some instances while the latter is better in some other instances.

III. MATHEMATICAL MODEL

We present the following model to resolve our problem. The objective is to provide a deployment scheme while optimizing the target coverage of the localization. To best locate, we aim to optimize the placement of nodes with the most possible uniform distribution of nodes (anchors and mobile nodes) around the target to locate. Among the considered constraints, the non-alignment of nodes and a well-studied distances between them. The set of targets to detect; the location of potential sites to install the sensors; the transmission power, the cost and the minimum number of received signals to detect a target are considered known in our model.

A. Assumptions

We set the following assumptions:

- Each anchor node is composed of two sensors (a bar containing two microphones), installed in such a manner that the bars of the different adjacent anchors are not aligned (Fig.1).
- Optimizing the localization considering that the target to be located must be within the audio range of at least two anchors nodes.
- There are two cases: either using two anchors, either using three anchors.
- When using two anchors, it is better to have a right angle between the two bars of microphones.
- When using three anchors, it is better that the mobile node is in the range of three anchors. Thus, each anchor must be oriented at 60 degrees with respect to each other.

B. Notation

The following notation is used in this paper. It is composed of sets, decision variables and parameters.

• Sets

- ✓ **T**: set of targets to detect in the field, t_k is a target.
- ✓ **N**: the set of different types of sensor nodes, $N = \mathbf{Na} \cup \mathbf{Nb}$.
Na, the set of different types of stationary nodes
Nb the set of different types of mobile nodes
- ✓ **S**: set of potential sites to install the sensor nodes $S = \mathbf{Sa} \cup \mathbf{Sb}$
Sa the set of potential sites to install the stationary sensor nodes, na is a site of a stationary node.

Sb the set of potential sites to install the mobile sensor nodes, nm is a site of a mobile node.
(a site may not be in both sets, that is, $\mathbf{Sa} \cap \mathbf{Sb} \neq \emptyset$)

• Decision Variables

- ✓ W_s^n be a 0-1 variable such that $W_s^n = 1$ if and only if a node of type $n \in N$ is installed at site $s \in S$
- ✓ X_{ts} , a 0-1 variable such that $X_{ts} = 1$ if the node of type $n \in N$ installed at site $s \in S$ receives a signal from a target at the position $t \in T$ with a power greater than or equal to the minimum required power by the node to detect it.
- ✓ $Sg_{ss'}$ is also a 0-1 variable such that $Sg_{ss'} = 1$ if and only if the node installed at site $s \in S$ receives a signal from another node installed at site $s' \in S$ with a power greater than or equal to the minimum required.
- ✓ $Sg_{ss'}^{mn}$, be a 0-1 variable such that $Sg_{ss'}^{mn} = 1$ if and only if the node of type $n \in N$ installed at site $s \in S$ receives a signal from another node of type $n' \in N$ installed at site $s' \in S$ with a power greater than or equal to the minimum required power.
- ✓ **Ms** is the minimum number of hops between a stationary node installed at site $s \in S$ to any mobile node.

• Parameters

- ✓ γ_{ts} be the signal attenuation ratio from the target $t \in T$ to site $s \in S$,
- ✓ $\delta_{ss'}$ the attenuation ratio between the sites $s \in S$ and $s' \in S$,
- ✓ P_t is the transmission power of a target at the position $t \in T$ (in watts).
- ✓ p_n is the transmission power of a node of type $n \in N$ (in watts).
- ✓ P_{\min}^n is the minimum power of a received signal by a node of type $n \in N$ to detect it (i.e. the sensibility).
- ✓ n_{\min} the minimum number of nodes receiving a signal from a target to localize it (in our case, $n_{\min} \in \{2,3\}$),
- ✓ hp_{\max} , the maximum number of hops between a anchor node and a mobile node,
- ✓ c_s the cost of a node of type $n \in N$ and installing it at site $s \in S$.
- ✓ Ag_{ij}^{m1m2} angle between two microphones $m1$ and $m2$ of two different and adjacent nodes i and j .

- ✓ n: length of the RoI (Region of interest).
- ✓ m: width of the RoI
- ✓ r: radius of a sensor (all the sensor nodes have the same sensing range).
- ✓ nbNa: number of stationary nodes
- ✓ nbNm: number of mobile nodes needed to add.
- ✓ nbT: number of targets
- ✓ Sg_{ij} : power of the signal transmitted between two nodes i and j.
- ✓ d_{ij} : distance between two nodes i and j,
- ✓ d_{m1m2} : a constant representing the distance between two sensors (microphones) of the same node.
- ✓ d_{max} : a constant representing the maximum distance between two nodes i and j (or a node i and a target j) so that they can be detectable.

C. Objective function

To model the problem of target coverage considering the localization, we consider the following objective function.

- Coverage: Let F1 be the fitness of a mobile node i (nmi) which calculates the coverage as a function of the targets it covered, we obtain the following function F1 for the coverage

$$F1 = \text{Maximize} \left(\sum_{n_m \in Nm} F(n_m) \right) \quad (1)$$

- Localization: each target must be monitored by at least n_{min} nodes (mobile or anchor), thus:

$$\sum_{s \in S} x_{ts} \geq n_{min} \quad \forall t \in T, \text{ we obtain the following}$$

function F2 for the localization:

$$F2 = \text{Maximize} \left(\sum_{t \in T} \left(\sum_{s \in S} x_{ts} - n_{min} \right)^+ \right) \quad (2)$$

knowing that $(x)^+ = \max(0, x)$

Thus, the fitness function is given by:

$$\begin{aligned} F &= F1 + F2 \\ &= \text{Maximize} \\ &\sum_{t \in T} \left(\sum_{s \in S} x_{ts} - n_{min} \right)^+ + \sum_{n \in N} F(n_m) \end{aligned} \quad (3)$$

D. Constraints

F is subject to:

$$\sum_{s \in S} x_{ts} \geq n_{min} \quad \forall t \in T \quad (4)$$

$$Sg_{ts} = 1 \Rightarrow Ag_{ts}^{m1m2} = k\Pi / n_{min}, t \neq s \quad (5)$$

$$Sg_{ts} = 1 \Rightarrow \sum_{n \in N} Ag_{ts}^{m1m2} \in [0, k\Pi], t \neq s \quad (6)$$

$$nbNa = n_{min} \cdot (nm / 2\Pi r^2) \quad (7)$$

$$d_{ts} = \alpha \cdot Sg_{ts} \cdot g(Sg_{ts}), \alpha \in R \quad (8)$$

$$(Sg_{ts} = 1) \Rightarrow (d_{ts} \leq d_{max}) \quad (9)$$

$$\sum_{s \in S} x_{ts} \leq \sum_{n \in N} W_s^n \quad (10)$$

$$\delta_{ss'} \sum_{n \in N} P^n \sum_{n' \in N} Sg_{ss'}^{nn'} \geq \sum_{n' \in N} P_{min}^{n'} \sum_{n \in N} Sg_{ss'}^{nn'} \quad (11)$$

$$Sg_{ss'} = \sum_{n \in N} \sum_{n' \in N} Sg_{ss'}^{nn'} \quad (12)$$

$$\delta_{ts} P_t \geq \sum_{n \in N} P_{min}^n W_s^n, \quad \forall t \in T, s \in S \quad (13)$$

The objective function (3) of the problem aims to optimize the target coverage and the localization. **Constraint (4)** impose that the number of nodes receiving a signal from the target i must be greater than or equal to the minimum necessary to localize it. **Constraint (5)** force the angles of arrival between sensors (microphones) $\alpha + \beta = \chi$ to be 90° in the case of 2-coverage ($n_{min}=2$) and to be 60° in the case of 3-coverage ($n_{min}=3$). **Constraint (6)** concerns the non-linearity of the adjacent nodes in order to optimize the localization. **Constraint (7)** imposes the number of the anchors deployed initially. **Constraint (8)** link the distance and the power transmission of the signal between two nodes. g is a function, α is real coefficient. **Constraint (9)**, imply that if there is a signal Sg_{ts} between two nodes, the distance between these two nodes (d_{ij}) should not exceed a fixed maximum distance (d_{max}). **Constraint (10)**, impose that a target cannot be detected by a number of nodes that exceeds the number of installed nodes in the different sites. **Constraint (11)** impose that if the node s' is detected by the node s , then the power transmission resulting from s towards s' must be higher than the minimum necessary power transmission so that s is detectable by s' . **Constraint (12)** concerns the power transmission emitted by the node s and received by the node s' , for different types of nodes. **Constraint (13)** indicate that the node installed at site s must receive a signal from a target at position t with a power greater than or equal to the minimum required to detect it.

IV. TARGET LOCALIZATION

Let's consider a mobile source emitting a sound $s(t)$ and a node equipped with two microphones. Each one of the two microphones is receiving a signal ($s_1(t)$ for the first and $s_2(t)$ for the second). Due the distance between the two microphones, a difference of time between the observations of the sound signal will be noted at each microphone, referred to as Time difference of Arrival. TDoA (Fig.1) is computed using the spatial positions of the target and microphones.

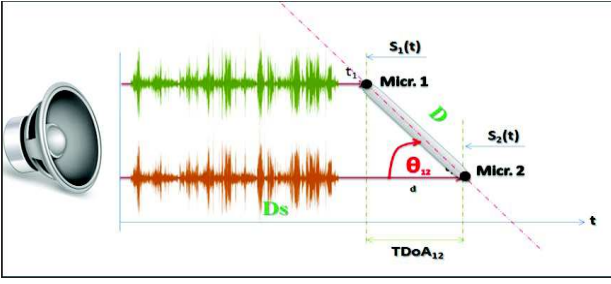


Fig. 1. Time Difference of Arrival (TDoA)

Acoustic localization is done following two major steps; The first step consists on estimating the time difference of arrival (TDoA) of the signals captured by two separated microphones of one node. Then, the direction of arrival of the sound with respect to this node is computed using trigonometry specifications. The second step consists on localizing the acoustic source using at least two nodes. The process consists on merging the results obtained with each node in term of direction of arrival and then use a specific geometric positioning method in order to compute the geometric coordinates of the acoustic source in a 2D space

V. A GENETIC ALGORITHM FOR THE DEPLOYMENT CONSIDERING THE TARGET LOCALIZATION

In this section, we present the suggested approach. We present the assumptions of the network, the coverage model, and we discuss the approach based on the genetic algorithm.

A. Network Assumptions

We assume that the sensor nodes are randomly deployed and the number of sensor nodes initially deployed is equal to the required number to achieve n_{min} -coverage ($n_{min} \in \{2,3\}$) as if these nodes were deterministically deployed. We also assumed that mobile nodes are used to repair the coverage holes after the initial deployment of the stationary nodes.

B. Coverage Model

We assume that each sensor node has a sensing radius r which covers a circular area. We also assume that a target t_k can be detected by the sensor S_i if t_k is within the sensing range of S_i . We also assumed that d is the distance between the target object being sensed t_k and the sensor node S_i . The coverage function $Coverage(S)$ is equal to 1 if the target object can be sensed and covered; otherwise it is equal to 0. This binary model of sensor detection can be represented as follows:

$$Coverage(S) = \begin{cases} 1, & d(S_i, t_k) \leq r \\ 0, & d(S_i, t_k) > r \end{cases}$$

C. The Proposed Genetic Algorithm (NSGAI)

We aim at maximizing the coverage rate by reducing the holes, and maximizing the localization.. Assuming that S_i is the stationary sensor nodes deployed randomly over the region of interest, r is the sensing range of the sensors. The proposed genetic algorithm starts with an initial random population (the distribution of the initial nodes). Then, the objective function evaluates in each iteration the constraints satisfaction rate. The new solution (population) is improved after each iteration of the algorithm. This improvement is carried out through the

operators (crossover and mutation). A stopping criterion is used to stop the execution of the algorithm. The genetic algorithm is run by the base station after gathering the positions of the stationary nodes in order to determine the number and positions of the mobile nodes as follow:

• Representing a chromosome

In the proposed genetic algorithm a chromosome represents a solution that indicates the position (location) of a potential mobile node in the region of interest (RoI). This position is modeled as an (X, Y) point. The different gens of the chromosome represent a binary digit that resembles the value of the position on the X and Y axes. For example, to represent a mobile node mapped to the location $(50, 65)$, the corresponding chromosome is shown in Fig.2. The Choice of the size of the chromosome population is based on two factors: the area of the RoI and the initial configuration of the network. For instance, if the radius of each node is 48m and the area of the sensing field is $70 \text{ m} * 80 \text{ m}$, the number of deployed stationary nodes will be (i.e.; $(70*80)/(\pi*48^2) \approx 117$), then the algorithm will start with population of 117 randomly generated chromosomes to ensure the full coverage. The value 117 is selected based on the assumption that 117 sensor nodes would cover the entire field as if they were deterministically deployed. If we aim to ensure a k -coverage (each target must be covered by at least k sensor nodes), we have to start with $117 * k$ chromosomes as an initial population.

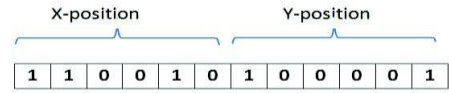


Fig. 2. Chromosome representing the sensor position $(50, 65)$

• Evaluation

After the initialization, each chromosome fitness (i.e.; the goodness of the solution) is evaluated using the fitness function. The fitness or the formulation of the objective depends on characteristics of the problem. The fitness function is used to choose the best fittest chromosomes to reproduce the next generated solutions by the algorithm. The fitness function calculates the maximum number of the covered targets by each mobile node. The overlapping redundancy is prevented by the fitness function among the coverage regions of the deployed mobile nodes. The fitness function is given by:

$$F = \text{Maximize} \left(\sum_{t \in T} \left(\sum_{s \in S} x_{ts} - n_{min} \right)^+ + \sum_{n \in N} F(n_m) \right) \quad (14)$$

• Reproduction

Reproduction is composed of four steps: selection, crossover, mutation, and accepting the solution. The fitness is used as a measure to rank the chromosomes and to perform parent selection according to the ratio participated by each chromosome in the fitness function in order to reproduce new solutions. However, less fitness members will have also a chance to be selected. Different mechanisms are used to implement the selection step such as the rollet wheel method. The selection will be performed on two chromosomes to reproduce two new chromosomes each time. After selecting the chromosomes, a crossover operation is performed between a

pair of parent chromosomes by selecting a random point in chromosomes and exchanging genes after this point. We choose two random crossing points. The child inherits elements positioned between the two crossover points of the first parent. These elements occupy the same positions, and appear in the same order in the child. The selection and crossover operations may lead to a set of identical chromosomes and the algorithm stops creating new individuals. This may prevent the average fitness improvement and thus trapping into a local optimum. To avoid this problem, a mutation operation is applied where a gene is selected randomly and its value is changed. Mutation performs a larger exploration of the search space, to avoid the premature convergence or the disappearance of the diversity while bringing innovation to the population. The mutation is carried out by reversing the position of two genes. Often, each gene is represented by a bit; the mutation is done by flipping a bit randomly in the chromosome. After crossover and mutation, two new chromosomes are reproduced. Finally, if they are better than their parents, they will be accepted as a new population.

• **Stopping Criterion**

The stopping criterion is either reaching a maximum number of iterations; either reaching a predefined localization rate (if a rate of k-coverage is ensured, $k = n_{min}$). Also, we can use a maximum execution time of the algorithm as a stopping criterion.

VI. EXPERIMENTAL RESULTS

In this section, we evaluate the performance of the proposed genetic algorithm in terms of the amount of coverage (coverage rate), the degree of coverage (k-coverage), the number of iterations, and the pareto front. We use the following parameters for the genetic algorithm:

- Area of Simulation ($n \times m$) = 200x300.
- Maximum number of generation = 350.
- Size of population (number of mobile nodes) = $\frac{nm}{2\pi r^2}$.
- Number of initial stationary nodes = $\frac{nm}{2\pi r^2}$.
- Probability of mutation = 0.1.
- Probability of crossover = 0.8.
- Number of constraints = 10.

The following figures (Fig.3, Fig.4 and Fig.5) show the difference, in terms of coverage rate between the initial random coverage and the coverage rate ensured by our algorithm.

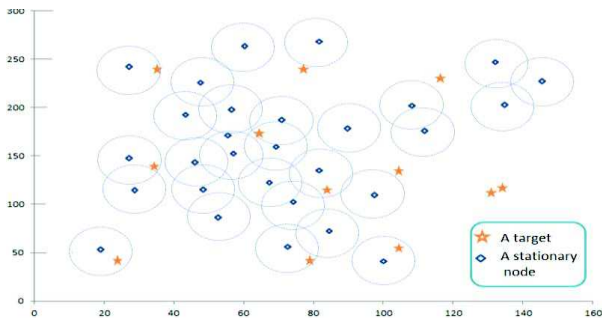


Fig. 3. Initial Random Deployment

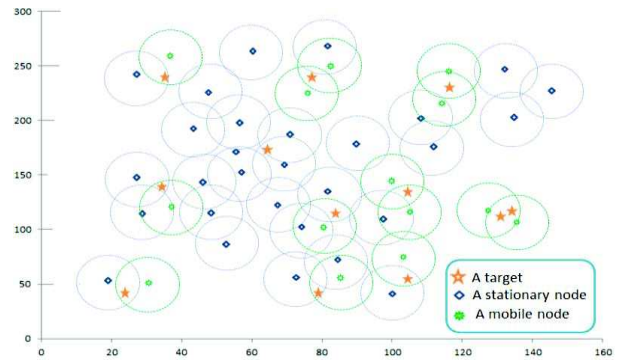


Fig. 4. Deployment after executing the GA for the 2-coverage case

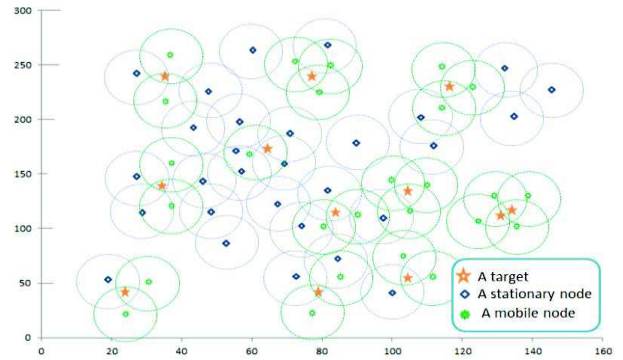


Fig. 5. Deployment after executing the GA for the 3-coverage case

The following Fig.6 represents the coverage rate (axis y) when increasing the number of iterations (axis x). This figure shows that the coverage rate improves when increasing the number of iterations until reaching the demanded degree of coverage.

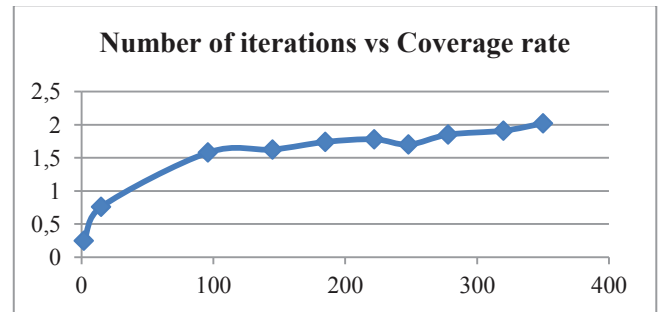


Fig. 6. Number of iterations vs the coverage rate for the 2-coverage case

Actually, our aim is to better locate an acoustic source (target) using genetic algorithm. In fact, as discussed in [8], audio localization performance depends on distance between nodes and the target. In order to perform audio experimentations, we considered an array of two pairs of microphones (as two nodes), two computers, one Smartphone emitting a continuous sound.

Every node is hooked to a computer. We place the Smartphone in an already known position. We then compute for node the angle of arrival of the sound emitted by the Smartphone (as the target). The obtained values of the two angles are automatically stored in order to be used to determine the geographic position of the sound source (Fig.7).

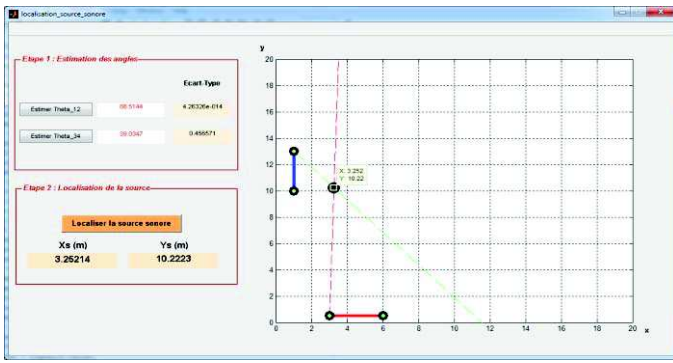


Fig. 7. Screen shot of the developed application for step 2

As we can see in Table I and Fig.8, the error between the estimated positions and the real ones can be explained by the assumptions we had made.

TABLE I. EXPERIMENTAL RESULTS

Real angles (°)		Real positions (m)		Estimated angles (°)		Estimated positions (m)	
θ_{12} theo	θ_{34} theo	X theo	Y theo	θ_{12} esti	θ_{34} esti	X esti	Y esti
90	45	1	1.3	94.15	39.03	0.946	1.25
90	135	1	2.3	95.9	135.048	0.831	2.132
90	90	1	1.8	84.078	89.554	1.13	1.79
45	45	1.4	0.9	44.61	41.77	1.35	0.84
45	90	2.3	1.8	53.28	87.38	1.92	1.735

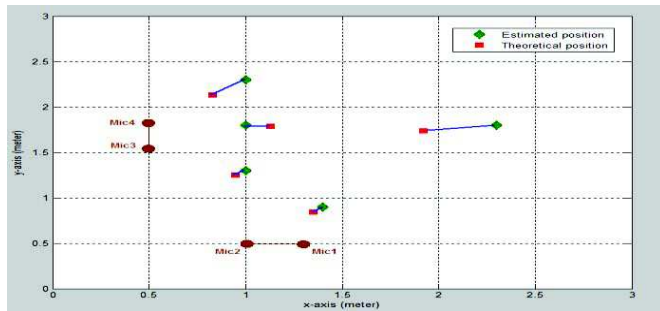


Fig. 8. Acoustic source estimated positions vs theoretical positions

For a multi-objective problem, there is no single solution. The goal of the multi-objective genetic algorithm is to find a set of solutions in that range (ideally with a good spread). The set of solutions is also known as a Pareto front. All solutions on the Pareto front are optimal. In the case of bi-objective problems, informing the decision maker concerning the Pareto front is usually carried out by its visualization. The Fig.9 shows the pareto front of the genetic algorithm. In Fig.9, the x axis represents the values of the first objective function F1 while the axis y represents the values of the second objective function F2.

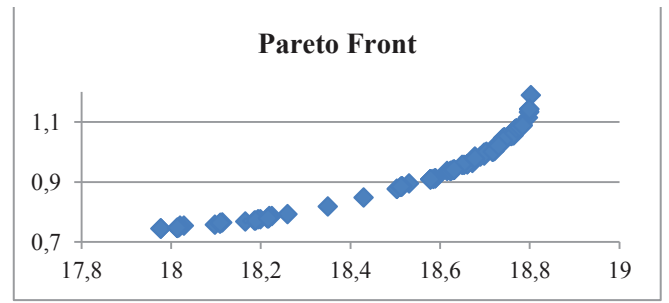


Fig. 9. The Pareto Front of the genetic algorithm

VII. CONCLUSION

In this paper we are interested in deploying a wireless audio-sensor network to optimize coverage and audio localization. We provided a genetic algorithm for an optimized placement of audio-sensor nodes. The aim is to propose an optimal solution for nodes deployment guaranteeing the following objectives: maximizing the coverage area, maximizing the precision audio localization at the level of the detection signal. The proposed genetic algorithm show significant performance improvement in quality compared to the random deployment and the existing methods. As a prospect of our study, we aim to optimize the proposed algorithm in order to ensure the redeployment problem while optimizing different objectives other than the coverage and the localization, such as the lifetime and the network connectivity. Also, we aim to test our contributions by simulation and in reality on a set of testbeds of the OpenWiNo emulator, deployed to the IUT of blagnac in Toulouse.

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