The Coverage Problem in Wireless Sensor Networks by Holonic Multi-Agent Approach

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Abstract:
A wireless sensor network will collaborate for a common application such as environmental monitoring. One fundamental issue in sensor networks is the coverage problem. We present in this article a Holonic Multi-agent approach that solves the coverage problem when using wireless sensor networks. Complex systems are characterized by large number of entities in interaction, exhibiting emergent behaviors. The holons in holonic multi-agent systems are not required to coordinate the work of a physical resource, but instead may coordinate the work of several information agents that only exist virtually. A super-holon is, internally, a community of holons that cooperate to achieve a commonly agreed objective or task. On the other hand, Multi-Agent Systems (MAS), stand out as a paradigm for the design of Complex Systems.

Categories and Subject Descriptors: C.2.1 [**Network Architecture and Design**]: Wireless communication; I.6 [**Simulation and Modeling**]: Applications
General Terms: Agent, clustering, coverage, holon, modeling, multi-agents, sensor

Additional Key Words and Phrases: coverage problem, Holonic organization, Holonic multi-agent systems, sensors network

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1. INTRODUCTION

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A sensor is an equipment which has the capability to perceive the environment where it is established or the phenomenon that justified its implementation. It must also be able to transmit the perceived data. Such sensors are called scalar sensors.

There exist other types called multimedia sensors. They include the equipments that are able to perceive and broadcast audio streams, video streams, or fixed images.

A wireless sensor network is composed of a great number of sensors, deployed massively for the observation of a phenomenon [Akyildiz et al 2002]. Since sensors may be spread in an arbitrary manner, one of the fundamental issues in a wireless sensor network is the coverage problem.

In MeguerdichianS et al. [2001], localized exposure-based coverage and location discovery algorithms are proposed, a sensor coverage metric called surveillance that can be used as a measurement of the quality of service provided by a particular sensor network. Their approach consists in combining computational geometry and graph theoretic techniques, such as Voronoi diagrams and graph search algorithms.

In the literature, this problem has been formulated in various ways, for example: as a decision problem, whose goal is to determine whether every point in the service area of the sensor network is covered by at least k sensors, where k is a predefined value [Chi-Fu and Yu-Chee 2003]. The coverage can be considered as the measure of the quality of service of a sensor network. For example [Meguerdichian et al 2001], in a fire detection sensor networks example, one may ask how well the network can observe a given area and what the chances are that a fire starting in a specific location will be detected in a given time frame.

In [Mihaela and Jie 2006], the most discussed coverage problems in literature can be classified into three types: area coverage, point coverage and barrier coverage. The barrier coverage consists in minimizing the probability of undetected penetration through the barrier (sensor network). In the point coverage problem, the objective is to cover a set of points. In the area coverage problem, the main objective of the sensor network is to cover an area or a region.

We focus on the area coverage problem, and we suppose that a set of sensors is arbitrarily distributed in an area. The nodes proceed to deploy themselves in such a way that they maximize the covered area. We propose an approach based on a Holonic Multi-Agent System (HMAS) organization.

Our motivations in using HMAS are twofold. A sensor network is an open system composed of autonomous sensor nodes. They are autonomous, spatially organized and they have to form groups in order to efficiently collaborate. In the holonic approach, a group can behave like one atomic entity; therefore we can build the patrol of sensors using the holonic concept.

The remainder of this paper is organized as follows. In section 2 are presented the related works on the coverage problem. In section 3, the holonic multi-agent systems are described and a clustering algorithm for the construction of our holonic organization is proposed. The coverage problem in wireless sensor networks is presented in section 4. Concluding remarks and future research directions are given in section 5.

2. The coverage problem

One of the fundamental issues that arises in sensor networks, in addition to location calculation, tracking, and deployment, is coverage. Due to the large variety of sensors and applications, coverage is subject to a wide range of interpretations. The coverage can be deterministic or stochastic. In the first case, the predefined locations of the sensors can be uniform in different areas of the sensor field. The problem of coverage of the sensor field reduces to the problem of coverage of one cell and its neighborhood due to the symmetric and periodic deployment scheme. In the second case, the sensors are randomly distributed in the environment. The stochastic random distribution scheme can be uniform, Gaussian, Poisson or any other distribution based on the application at hand [Meguerdichian et al 2001]. MeguerdichianS et al. [2001] have assumed a centralized control server, where nodes are connected using a gateway. For the context of coverage, resolution strategies and negotiation are needed to integrate information from this stage to be used in related contexts such as tracking mobile objects in the network and handling obstacles.

[Chi-Fu and Yu-Chee 2003] formulate this problem as a decision problem, whose goal is to determine whether every point in the service area of the sensor network is covered by at least k sensors, where k is a predefined value. Chi-Fu et al. [2004] formulate the coverage problem as a decision problem, whose goal is to determine whether every point in the service area of the sensor network is covered by at least α sensors, where α is a given parameter and the sensing regions of sensors are modeled by balls (not necessarily of the same radius). He shows that tackling this problem in a 3D space is still feasible within polynomial time. The proposed solution can be easily translated into an efficient polynomial-time distributed protocol.

Xiang-Yang et al. [2003] give efficient distributed algorithms to optimally solve the best-coverage problem raised in MeguerdichianS et al. [2001]. They are interested in designing a localized algorithm that finds a path connecting a point and a point t, which maximizes the smallest observability of all points on the path. They are called the best coverage problem. In [Mihaela and Jie 2006], the sensor coverage problem has received increased attention recently. This problem is centered around a fundamental question: How well do the sensors observe the physical space? The most discussed coverage problems in literature can be classified in the following types: area coverage, point coverage and barrier coverage. He considers the barrier coverage as being the coverage with the goal of minimizing the probability of undetected penetration through the barrier (sensor network). In the area coverage problem, the main objective of the sensor network is to cover (monitor) an area (also referred sometimes as a region), each point of the area is monitored by at least one sensor. In the point coverage problem, the objective is to cover a set of points (i.e., a set of sensors randomly deployed to cover a set of points).

3. HIERARCHICAL STRUCTURE, CLUSTERING AND HOLONS

3.1 Holon and clustering

In Multi-Agent Systems, MAS for short, stand out as a paradigm for the design of Complex Systems. Indeed, this paradigm proposes new strategies for the analysis, modeling and implementation of such systems. Its elementary constituents are called 'agents', i.e. software entities which exhibit autonomous and flexible behaviors [Sebastián 2005]. In MAS, an agent is a physical or virtual entity [Ferber 1995]. Agents are not necessarily composed of other agents, while holons are, by definition, composed of other holons, referred as the super and sub-holons.

The holon term was introduced by the Hungarian philosopher Arthur Koestler in 1967. Arthur Koestler coined the term holon as an attempt to conciliate holistic and reductionist visions of the world. A holon represents a whole-part construct that can be seen as a component of a higher level system or as a whole composed of other holons as sub-structures.
In its initial idea, it refers to a natural or artificial structure; its direction is not absolute. According to Koestler, a holon must observe three conditions: (1) be stable, (2) have a capacity of autonomy, (3) be able to cooperate.

Stability means that the holon must be able to react well when strong disturbances occur. Autonomy means that the holon must be able to be self-managed in order to achieve its goals. Cooperation means that the holon must be able to work jointly in a project, the goals being divided with the other holons or the other layers of holons.

A holon is a self-similar structure composed of holons as sub-structures. A hierarchical structure composed of holons is called a holarchy [Rodriguez et al. 2007]. The Holonic Organization (HO) represents the organization of a single super-holon at a specific level in the holarchy [Rodriguez et al. 2003].

The concept of Holon is specialized from the Agent [Cossentino et al. 2007]. This definition of holon integrates the production and holonic aspects, the approach being described as organizational. An agent in our approach defines a particular context of interaction between roles belonging to different organizations. This aspect is depicted in Figure 1.

Figure 1. Atomic Holon (Agent)

A holon can play several roles in different organizations and can be composed of other holons. A composed holon is called super-holon. It contains at least a single instance of a holonic organization to precise how members organize and manage the super-holon.

It also contains a set of production organizations describing how members interact and coordinate their actions to fulfill the super-holon tasks and objectives.

An illustration of the definition of holon is depicted in Figure 2.

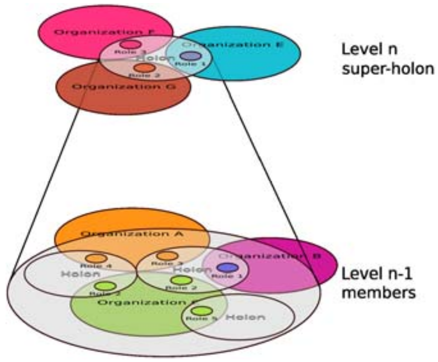

Figure 2. Holon

The holonic aspect considers how members organize and manage the super-holon. A specific organization, called Holonic organization, is defined to describe the management of a holon and its structure.

Depending on the level of abstraction, a super-holon can be considered as an atomic entity (at level n) or as an organization of holons (at level n-1) [Cossentino et al. 2007].

The clustering consists of a virtual network division in geographically close groups of nodes [Mitton 2006]. These groups are called clusters. They are generally identified by a particular node called cluster-head (or chief of group). In the majority of clustering algorithms, the clusters are built using a particular metric which makes it possible to assign a head with each cluster; the cluster is then formed of the cluster-head and of all the nodes which are attached to it.

3.2 Construction of the holonic organizations

Assumptions

- There are some assumptions.
- Every sensor node has one unique ID.
- Every sensor node can sense and communicate in some range.
- Direct sensor node’s communication range is equal to sensing range.
- Every sensor node can detect and send messages to another node within communication range.

Mobile wireless sensors are here used to ensure a dynamic coverage of areas. With the aim of building our holonic organization, we propose the following approach.
A priori, a holon is a sensor or a set of sensors.

Let us define:

C_i : sensor identifier i
CH_i : field of sensor C_i
D : set of communicational distance in the holarchy

Definition:

The field (CH_i) of a sensor is the area in which the emitted signal has a non-zero power.
Any sensor $C_k \in CH_i$ (with $C_k \neq C_i$) will be in the vicinity of C_i
In order to form D, if we suppose a sensor C_i and his coverage radius r_i, then we define $d_k=k*r_i$ for a given k, d_k defines a communicational distance of C_i in the holarchy.
Let us consider the set V_i of sensors located in the communicational neighborhood of the sensor C_i. D is the set of the distances d_k from C_i to each sensor of V_i. Hence $D=\{d_1, d_2 \ldots d_h\}$.
The set D_n of the sensors of distance $d_{n-1} \leq d(Ci, Cj) \leq d_n$ are of range n.

Algorithm for building the holonic organization:

Initially, build up the set of cluster using the concept of neighborhood as the metric (by the distance between sensors) and accessibility (ability to receive data from another), with or without a hierarchy according to the energy level
Thus, in an organization, a holon will be formed:
Either from a sensor having a specific energy level.
Or a set of sensors including energy belonging to a certain range.
The holon with the most energy may be present at the top of the hierarchy. This one must ensures the densest class of the traffic.
Initially, each cluster is considered as a holon
Within each organisation, optimize locally the coverage (the organization can use for example the repulsion model)
The local optimization involves the dynamic holon described below.

A holonic organization provides two major functions:

- the communication function
- the coverage function

At a holon will be involved a class of traffic. If the correspondent holon does not exist, then a higher level holon or a lower level holon will be requested according to the energy required by the traffic. A holon can move from one energy level to another, as it gains or loses energy.

Dynamic holons:

The satisfaction measures the progress of the holon towards achieving its current goal. The term Satisfaction has been often used to represent the gratification of an agent concerning its current state or the progress of its goals tasks [Simonin and Ferber 2001; Sebastián 2005]. The compatibility of two holons means that they can help each other to attain their goal. Two holons are compatible if they shared goals and complementary services.

The process of merging allows the creation and the integration of a new super-holon in the system.
The new super-holon can be created:

- either from an existing set of holons,
- or by decomposing a holon into sub-components.

In Figure 3 (a), the agents C_i, C_j and C_k in an holonic organization (OH) move according to the direction force $\vec{F}_{kji}$, $\vec{F}_{ikj}$, and $\vec{F}_{ijk}$

These direction forces represent the gradients between sensors, which graft in coalition.
This figure presents a repulsion model between three agents. The agent C_m will enter in the coalition if it arrives to communicate with at least one agent of the organization. In this case, their directional forces will be modified, and a new holon is generated in the system by the process of merging.

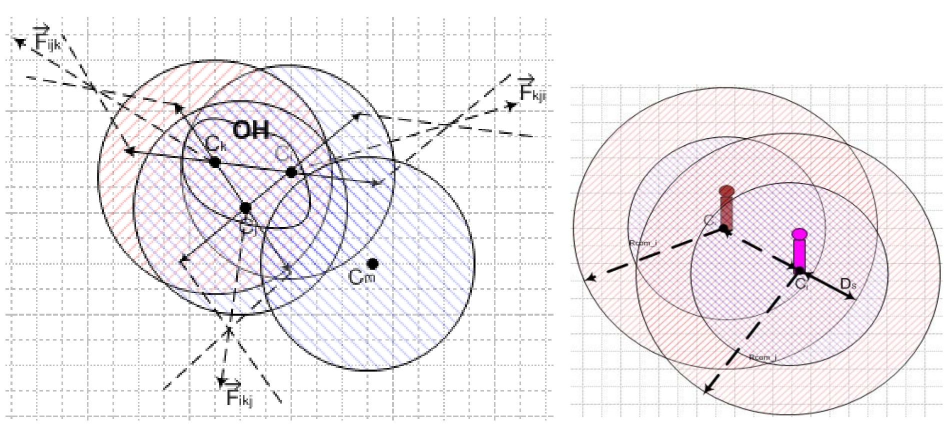

Figure 3. (a) Repulsion model (b) Boundary condition repulsion

The repulsion model force has a boundary condition. If the sensors are identical and the communications are full-duplex, then the sensors are put moving until $d(C_i,C_j) \geq R_{com}-\Delta_s$ with $\Delta_s \in R_+$, otherwise we have two cases:

- Full-duplex communications: $d(C_i,C_j) \geq Min(R_{com\_i}, R_{com\_j})- \Delta_s$ with $\Delta_s \in R_+$
- Unidirectional communications: $d(C_i,C_j) \geq Max(R_{com\_i}, R_{com\_j})- \Delta_s$ with $\Delta_s \in R_+$
- where R_{com} is the communicational radius of the sensor.

4. Coverage problem in the wireless sensors networks

4.1. Coverage of two sensor agents

Let us consider two sensors C_i and C_j of cover ray r_i and r_j respectively.
The distance from C_i to C_j is noted $d_{ij} = d(C_i, C_j)$.
Two situations can be met and are illustrated in the figures below:

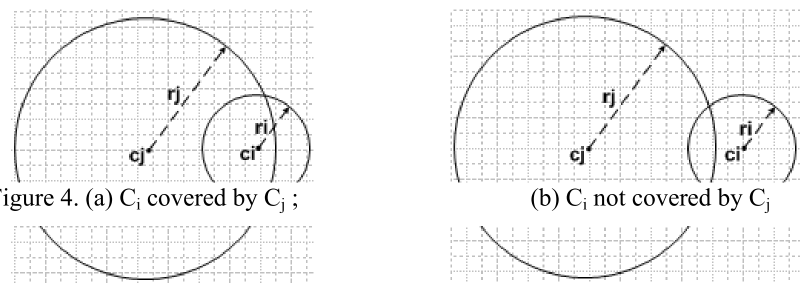

Figure 4. (a) C_i covered by C_j ; (b) C_i not covered by C_j

In case a), sensor C_i is accessible by C_j and can consequently retransmit data coming from C_j.
In case b), the sensor C_i is not directly accessible by C_j. Thus, they will need a relay C_{ji}. The position of the C_{ji} relay is in such a way that it can receive from C_j and reach C_i, and vice versa.

To have a set of sensors C_k in its communicational field, a sensor C_j must calculate L_k. The following formula describes how to determine L_k:

$$L_k = \bigcup_{h=1}^{k} D_h \quad with\ k \leq N, \text{ N is the maximum range defined by the holarchy.} \qquad (1)$$

Consequently: The communicational field of a sensor agent in the holarchy stretches to an arbitrary level.

Lemma 1:
After a sensor agent processes the corresponding algorithm, if L_1 is empty, then L_k ($k \geq 1$) will also be empty.

Proof:

If L_1 is empty, there is no sensor of range 1 in the field of C_j, and in consequence of range 2, …, k. Therefore L_k will be empty.

Lemma 2:
After a sensor agent processes the corresponding algorithm, if L_1 is empty, then the C_j sensor will be isolated from sending and not necessarily receiving data.

Proof:

According to the lemma 1, L_1 empty implies L_k empty. Consequently, there is no sensor in the field of C_j. Thus, the C_j sensor is isolated from sending. In this case, if it is within the sensing range of a sensor of greater radius, it will not be necessarily isolated from receiving data.

Let us consider two sensors C_i and C_j with coverage radii r_i and r_j respectively. As shown in the figure below, the common surface coverage is defined by:

$$S_{ij} = r_i^2 * \square + r_j^2 * \arcsin(r_i * \sin(\square)/ r_j) - r_i * \sin(\square) * (r_i * \cos(\square) + r_j * \cos(\arcsin(r_i * \sin(\square)/ r_j))) \qquad (2)$$

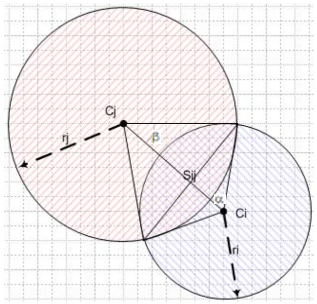

Figure 5. Common surface Coverage

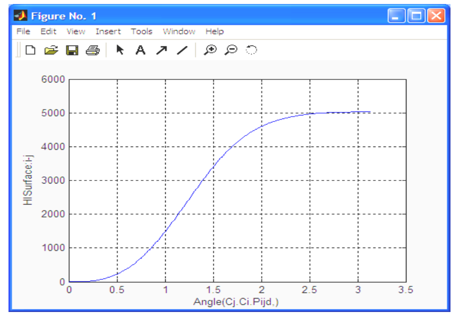

Figure 6. Execution Curve

For given r_i and r_j, the performance of the equation (1) gives us the curve of Figure 6.

Let us define S_i and S_j the respective surfaces of sensors C_i and C_j. The coverage area of these two sensors will be defined by: $Z_{ij} = S_i + S_j - S_{ij}$
The execution curve of Z_{ij} for fixed r_i and r_j is depicted in Figure 7.

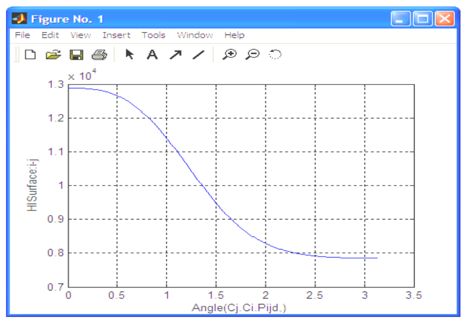

Figure 7. Execution Curve

4.2. Coverage of sensors network
Let us consider a network of N sensors. A sensor C_i has a coverage radius r_i.
Let us note HS the surface covered by the network,

$$HS = \sum_{i \in H} HS_i = \sum_{i=1}^{N} \left(S_i - \sum_{j=i+1}^{N} S_{ij} \right) \qquad (3)$$

H is the set of identifiers of holonic system.
S_i is the surface covered by a sensor.
S_{ij} is the common surface to both sensors C_i and C_j.

Definition:

Let VE_i, be the set of extended neighbours of the sensor C_i
A sensor $C_j \square VE_i$ if and only if $d(C_i,C_j) \square r_i+r_j$
where r_i and r_j are the coverage radii of sensors C_i and C_j respectively.
$d(C_i,C_j)$ is the distance between the sensors C_i and C_j

Proposition
Let VE_i, be the set of extended sensor C_i neighbours
Let VE_j, be the set of extended sensor C_j neighbours

if C_j VE_i then C_i VE_j
likewise : if C_i VE_j then C_j VE_i
(or) C_i VE_j if and only if C_j VE_i

Proof :

C_i □ VE_j □ $d(C_i,C_j)$ □ r_i+r_j

□ $d(C_j,C_i)$ □ r_j+r_i

□ C_j □ VE_i

Algorithm for estimating HS

An agent sensor C_i of a holonic organization H_k executes the following algorithm:

Determine the set of its extended neighbors VE_i
For each sensor C_j VE_i
add the coverage S_i to HS_k
if (r_i r_j) or ($r_i = r_j$ and $id_i < id_j$) then
- Evaluate the surface S_{ij}
- Remove S_{ij} to HS_k (HS_k=HS_k -S_{ij})
endif

Positioning and resolution of the coverage problem

The algorithm to be performed by each sensor C_i of a holonic organization H_k is as follows (case a):
Identify the set V_i of the sensors located in its field

For each sensor C_j V_i
1. Evaluate the moving direction (function of the sensor's force)
2. Evaluate the possible movement (this movement must respect the dynamics of the holon)
3. if ($r_i < r_j$) or ($r_i = r_j$ and $id_i > id_j$) then
Move following items 1 and 2
Update V_i
endif

To compare the behaviors of our organizations, the algorithm above were implemented in case b) with a slight difference in point 3.

if ($r_i > r_j$) or ($r_i = r_j$ and $id_i > id_j$) then
Move following items 1 and 2
Update V_i
endif

Simulation of coverage problem

Simulations were conducted with sixteen sensors, deployed randomly for area monitoring. The environment is continuous. The sensors are distributed randomly in a plane by reference {latitude, longitude, altitude} {(12 30 0) (12 33 0) (17 30 0)}. The coordinates (x, y) of the simulation environment are {(0,0),(800,0),(800,500)}.
The initial window implementation is as follows:

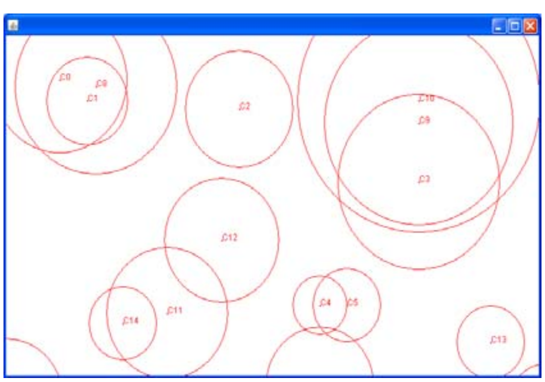

Figure 8. Initial window

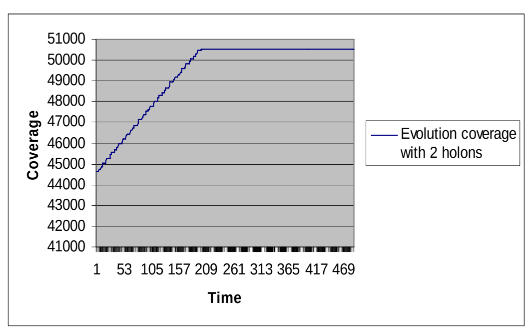

Figure 9. Coverage with 2 Holons

According to the above figure, the sensor C_{14} is in the sensor's field C_{11}. The sensor C_2 is isolated so it cannot send data to any sensors. From lemma 2, there are no sensors in the network able to perceive C_2. The sensors $C_{0,}$ C_1 and C_8 can send data from the one to the other.
After a dynamic discovery of the neighborhood and a relative positioning with respect to them, in case a: Figure 10 shows a coverage increase by 18%, and in case b: Figure 11 shows a coverage increase by 32%.
Thus, with a move of the sensor having the greatest radius of coverage, we obtain the best coverage.
The evolution of the surface (HS) covered by two holons of the network is depicted in Figure 9.

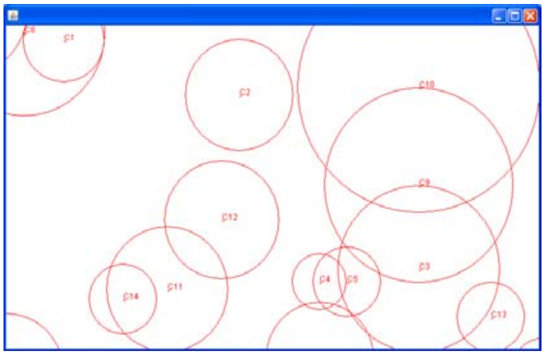

Figure 10. Relative positioning by smallest

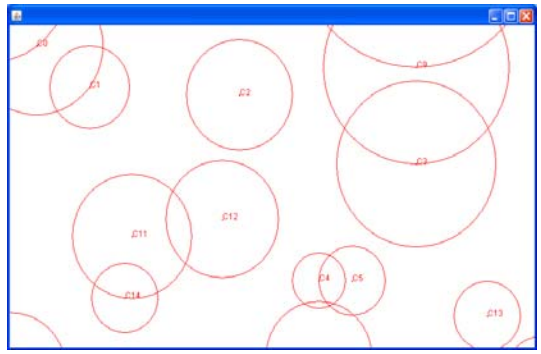

Figure 11. Relative positioning window

Thus, compared to its neighbors, the sensor having the greatest radius of coverage will move because it requires less energy. On equal radius of coverage, the one of greater identifier will move.
The simulation with 25 sensors, deployed randomly for area monitoring give the initial and final windows implementations as follows:

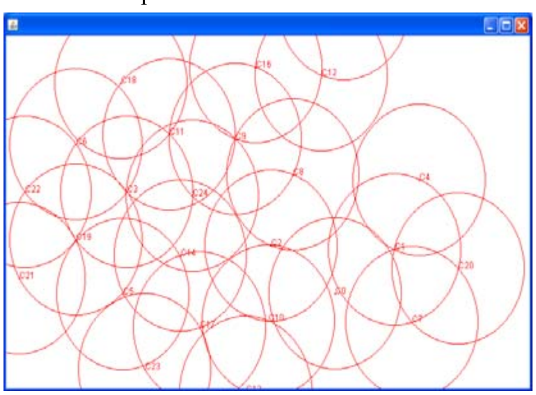

Figure 13. The final deployment of the sensor network with 25 nodes

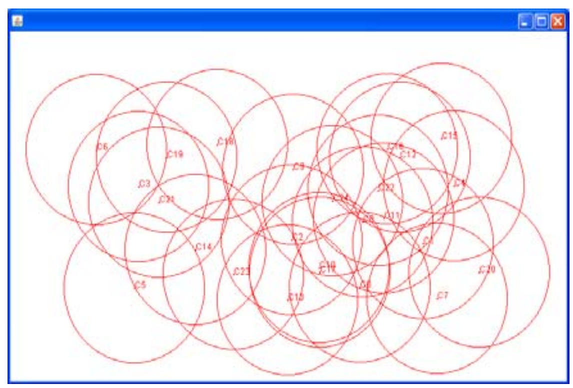

Figure 12. The initial deployment of the sensor network with 25 nodes

Figures 14 and 15 depict the coverage curve with 25 and 40 sensors, deployed randomly for area monitoring.

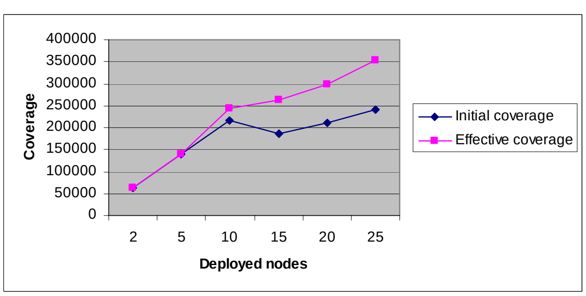

Figure 14. Coverage evolution with 25 sensors

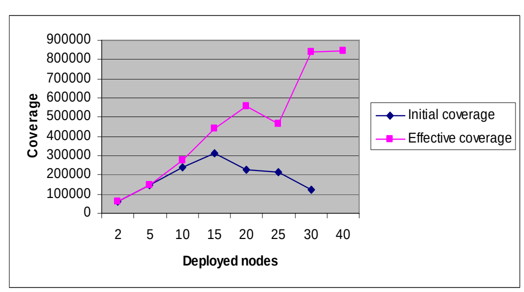

Figure 15. Coverage evolution with 40 sensors

5. CONCLUSION

We presented a network architecture of sensors by using the framework of the holonic multi-agent systems to deal with the coverage problem. A holon was defined as a set of roles according to various forms of organizational interactions in a specific context. We are currently working on these applications and extensions, and the related results will be reported in our future papers. As a short-term prospect, we intend to examine the simulation of some clustering methods on several instances of the coverage problem in order to validate our holonic multi-agent organization approach.

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