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

ELIE FUTE TAGNE
Department of Mathematics and Computer Science, University of Dschang, Dschang, Cameroon.

FABRICE LAURI & ABDER KOUKAM
Department of Computer Science, University of Technology of Belfort Montbeliard, Belfort, France.

EMMANUEL TONYE
Department of Electrical and Telecommunication Engineering University of Yaounde I, National Advanced School Of Engineering, Yaounde, Cameroon.

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.

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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.

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.

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](image)

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 \( i \)
- \( \text{CH}_i \): field of sensor \( C_i \)
- \( D \): set of communicational distance in the holarchy

**Definition:**

The field (\( \text{CH}_i \)) of a sensor is the area in which the emitted signal has a non-zero power. Any sensor \( C_k \) 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 \( d_k = k \cdot r_i \) 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 \( d_{n-1} \) to \( d_n \) 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 organization, 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 $F_{ijk}$, $F_{ikj}$, $F_{jki}$, and $F_{jki}$

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](image)

![Figure 3. (b) Boundary condition repulsion](image)
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 \( d(C_i, C_j) \geq R_{\text{com}} - \Delta_s \) with \( \Delta_s \in \mathbb{R}^+ \), otherwise we have two cases:

- **Full-duplex communications:** \( d(C_i, C_j) \geq \min(R_{\text{com}_i}, R_{\text{com}_j}) - \Delta_s \) with \( \Delta_s \in \mathbb{R}^+ \)
- **Unidirectional communications:** \( d(C_i, C_j) \geq \max(R_{\text{com}_i}, R_{\text{com}_j}) - \Delta_s \) with \( \Delta_s \in \mathbb{R}^+ \)

where \( R_{\text{com}} \) 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:

- **Case a):** Sensor \( C_i \) is accessible by \( C_j \) and can consequently retransmit data coming from \( C_j \).
- **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 \( L_k \):

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

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, \( \ldots, k \). 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:
\[ S_{ij} = r_i^2 + r_j^2 \cdot \arcsin(r_i \sin(\theta) / r_j) - r_i \sin(\theta) \cdot (r_i \cos(\theta) + r_j \cos(\arcsin(r_i \sin(\theta) / r_j))) \] (2)

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.

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 \( H_S \) the surface covered by the network,

\[ H_S = \sum_{i \in H} H_{S_i} = \sum_{i=1}^{N} S_i - \sum_{j=i+1}^{N} S_{ij} \] (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 \( C_j \in VE_i \) if and only if \( d(C_i, C_j) \leq r_i + r_j \)
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 \( C_j \in VE_i \) then \( C_i \in VE_j \)
likewise: if \( C_j \in VE_j \) then \( C_i \in VE_i \)
(or) \( C_i \in VE_j \) if and only if \( C_j \in VE_i \).
Proof:
\[ C_i \in VE_j \quad d(C_i, C_j) = r_i + r_j \]
\[ d(C_j, C_i) = r_j + r_i \]
\[ C_j \in VE_i \]

Algorithm for estimating HS
An agent sensor \( C_i \) of a holonic organization \( H_k \) executes the following algorithm:

1. Determine the set of its extended neighbors \( VE_i \)
2. For each sensor \( C_j \in VE_i \)
3. Add the coverage \( S_i \) to \( H_{Sk} \)
4. If \( (r_i < r_j) \) or \( (r_i = r_j \text{ and } id_i < id_j) \) then
5. - Evaluate the surface \( S_{ij} \)
6. - Remove \( S_{ij} \) to \( H_{Sk} \) (\( H_{Sk} = H_{Sk} - S_{ij} \))
7. 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):

1. Identify the set \( V_i \) of the sensors located in its field
2. For each sensor \( C_j \in V_i \)
3. 1. Evaluate the moving direction (function of the sensor’s force)
4. 2. Evaluate the possible movement (this movement must respect the dynamics of the holon)
5. 3. If \( (r_i < r_j) \) or \( (r_i = r_j \text{ and } id_i > id_j) \) then
6. Move following items 1 and 2
7. Update \( V_i \)
8. Endif

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

1. If \( (r_i > r_j) \) or \( (r_i = r_j \text{ and } id_i > id_j) \) then
2. Move following items 1 and 2
3. Update \( V_i \)
4. 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](image)

![Figure 9. Coverage with 2 Holons](image)
According to the above figure, the sensor C14 is in the sensor’s field C11. The sensor C2 is isolated so it cannot send data to any sensors. From lemma 2, there are no sensors in the network able to perceive C2. The sensors C0, C1 and C8 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.

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:

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

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.

6. REFERENCES:


