# A RIO Approach for Modeling Wireless Sensor Network

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## Abstract

*The goal of this paper is to bring forth a model for WSNs with the support of Holonic Multi-agent systems. In this paper, we not only introduce the RIO diagram to analyze the roles of sensor nodes during different periods of building up holonic architecture, but also present a self-organization scheme to construct a holonic architecture in WSNs. At last, performance analysis is proposed, including quantitative and qualitative analysis. Analysis result indicates that the hybrid architecture has the properties of scalability, distribution, long life-time and robustness.*

**Keywords:** RIO model, self-organization, wireless sensor networks.

## 1. Introduction

For a wireless sensor network, hundreds, and potentially thousands of low cost tiny sensor nodes are deployed in the interested fields(i.e., battlefield, forest) unattended, which often function autonomously (i.e., Zero-configuration, self-organization) without access to renewable energy resource. To the best of our knowledge, we could classify the application of WSNs into two classes. One is object tracking (i.e. monitoring war-field, etc.), specially mobile object tracking, the goal of which is how to let the sink achieving the location of mobile object from sensor nodes deployed in the interested field, the other is to measure the physical environment, the goal of which is how to get the environment physical information (i.e., temperature, air, water, soil and chemistry). Regardless of any application types above, WSNs must have the following characteristics from the viewpoint of organization under the consideration of the size constraint, energy constraint, and large scale of sensor nodes: (1) WSNs must have a goal, either to measure the physical environment or to track one or more objects. (2) No single sensor node can achieve the system's goal. (3) Many sensor nodes must act together to achieve a sub-goal, and total sensor nodes collaborate, even organize to achieve the system's goal more efficiently and/or accurately. (4) A single sensor node must change its internal state based on local stimuli, that is, the states of other near sensor nodes and its physical environment, Therefore, in large scale wireless sensor network, autonomous sensor nodes require to some extent the capability to group and collaborate, even organize to achieve shared objectives. The term holon was coined by Arthur Koestler in 1967 to explain social organization problems in human societies, which represents a part-whole construct see not only as a component of super-substructure from a higher level viewpoint, but also as whole composed of other holons as its substructures from a lower level viewpoint. Holonic systems grew from the need to find comprehensive construct that could help explain social phenomena and is used in a wide range of domains, including philosophy, manufacturing systems, and multi-agents systems [1~2].

The paper presents a framework that intends to provide a generic description of WSNs based on holonic system, which is a fundamental step towards a methodology in the formalization and validation of WSNs. Furthermore, we present a means to enable the self-organization of holons based on the joint degree of its members. We analyze the characteristics of WSNs and how these properties can be captured and reproduced using Holonic approach. An organization approach is used to model the structure of super-holon as well as the interaction that the members must undertake to achieve the fixed goals.

The remaining parts of this paper are organized as followings: Section 2 introduces the RIO model. An overview of the framework and the terminology used in this paper is presented in section 3. In section 4, performance analysis is proposed including quantitative and qualitative analysis. Finally, section 5 concludes this paper and discusses about some future researches.

## 2. RIO model

Since in the eighties, organizational approaches have been interested by researches, because there are

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some links between human organizations and computational systems [3]. The paper takes an organizational approach, that is, Role-Interaction-Organizational (RIO) model to analyze holonic system in WSNs. In RIO model a role is defined as "an abstraction of the behaviour of an agent" [4~6]. Otherwise, in WSNs the role has the following properties: (1) A sensor node is specified as an active communicative and/or computational entity (namely an agent). (2) A sensor node may play one or more roles and a role may be instantiated by one or more sensor nodes. (3) The relationship between roles and sensor nodes is dynamics. In other words, at any given time sensor nodes may request to play new roles and quit roles that it is currently performing.

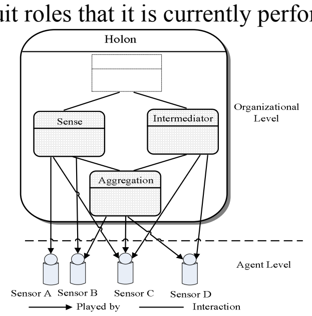


**Figure 1 RIO model in WSNs**

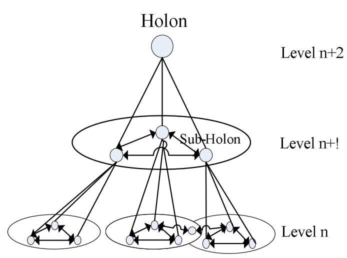


**Figure 2 A classical holonic structure**

The concept of interaction is defined in RIO model as how to link different roles in a way, and the third concept of RIO model is the organization that is an ensemble rather than collection of roles and their interactions[7~8]. In addition to its formal specification, RIO provides a graphical representation of organizations as in Figure 1. At the organizational level, we find only one organization *Holon,* which contains four roles, noted *Sense, Intermediator,* and *Aggregation*. To distinguish the environment role we use dashed lines in the RIO diagram. If all the sensor nodes receive the command from sink to complete a task, they will first play the role of *Sense,* that is, to measure the physical environment. If the furthest sensor nodes has received the data from other sensor node before transmitting its own original data, they will play another role(namely, *Aggregation*) except of *Sense*. The *Aggregation* role means that the sensor nodes will aggregate its own data and the data received from other sensor nodes into a new data, and transmit the result to its parent or its neighbour in order to reduce the length of data transmitted or the number of data in WSNs, as sensor B in Figure 1. If the furthest sensor nodes do not receive any data from other sensor nodes before transmitting its original data, they will play only one role (namely, *Sense*), as sensor B in Figure 1. In this paper, we call sensor A and B as orphan nodes. The sense nodes between orphan nodes and sink node, will play either three roles(namely, *Sense, Aggregation,* and *Intermediator*) or two roles(namely, *Aggregation,* and *Intermediator* ) in some application domains(i.e., object tracking). So call *Intermediator* role is that when sensor nodes receive data from other nodes, they must make a decision how to find the next link or rout. At the agent level we assign roles to agents (namely, sensor nodes in this paper). In fact sensor nodes instantiate and organization (roles and interactions) when they exhibit behaviours defined by the organization's role and when they interact following the organization interactions[1]. We call an instance of an organization a cluster. A sensor node may play one or more roles and a role may be instantiated by one or more sensor nodes. For example, sensor node C plays three different roles and the *Aggregation* role is played by three sensor nodes. Based on the RIO model we can now introduce our WSNs framework based on holonic Multi-agent systems.

## 3. Holonic framework in WSNs

In this section, we will introduce the holonic framework, deployment and self-organization scheme in WSNs.

### 3.1. Holonic Framework

A holon is a self-similar structure composed of holons as sub-structures. The hierarchical structure composed of holons is called a holarchy. A holon can be seen, depending on the level of observation, either as an autonomous "atom" entity, or as an organization of holons[1], A classical holonic structure is depicted in as Figure 2.

If we consider WSNs as a holon, we could say that the sink node could be considered as a super-holon from the viewpoint of the highest level[9]. Furthermore, the super-holon is composed several sub-holons which are its neighbours [10]. In turn, we can consider the neighbour node as a holon composed of its own neighbours. In order to meet the practical requirement in WSNs, we extend the classical holonic structure as another one which is depicted in Figure 3.

There are at least two differences between the extension holonic structure and classical holonic structure as following: (1) At every level, the sensor nodes are divided into smaller granularity, as we call it sub-cluster. As in Figure 2, at the n+1-th level, all the sensor nodes belong to only one cluster. However, in Figure 3 there is only one cluster composed of three sub-clusters at the n+1-th level, that is, a cluster (i.e., cluster 1) may comprise many sub-clusters. (2) There is no intersection between different clusters at the same level in Figure 3, that is, sensor nodes in different clusters could not communicate with each other directly, but they could communicate with each other through the sensor nodes at the higher layer as a coordinator. For example in Figure 3, Sink is the coordinator of different clusters at the n+1-th level, however, the sensor nodes at the n+1-th are the

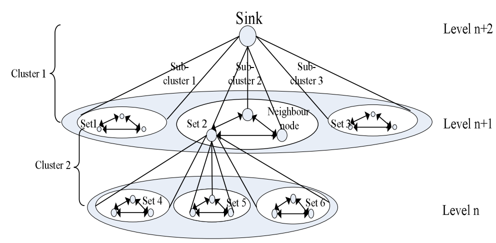


**Figure 3 Extension holonic structure in WSNs**

coordinators of different clusters at the n+1-th level.

### 3.2. Depoyment model of WSNs

In this paper, we only consider a general model of WSNs, supposing that N sensor nodes are deployed evenly in a circle region around the centre of sink node. A is the area covered by all the sensor nodes. The distance of the farthest sensor node to the sink is R .Clearly, A equals $\pi R^2$ . The send and receive ranges of each sensor node are all $r$ as in **Figure 4**.

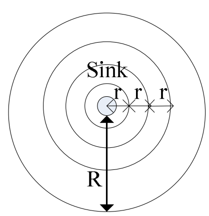


**Figure 4 Deployment model of WSNs**

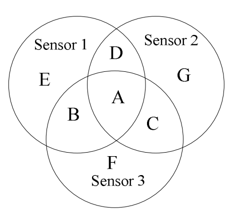


**Figure 5 Intersection of transmission range**

### 3.3. Radio model

In order to compute the real distance from sensor node to the sink, we introduce the same radio model as discussed in [14] which is the first order radio model. In this model, a radio dissipates $E_{elec}$ = 50 nJ/bit to run the transmitter or receiver circuitry and $\varepsilon_{amp} = 100 pJ/bit/m^2$ for the transmitter amplifier. The radios not only have power control and can expend the minimum required energy to reach the intended recipients, but also can they be turned off to avoid receiving unintended transmissions. $d^2$ energy loss is used due to channel transmission to calculate transmission costs and receiving costs for a $k$-bit message and a distance $d$ are shown as below Formula (1) and (2).

**Transition energy consumption**

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d)$$

$$E_{Tx}(k,d) = E_{elec} \times k + \varepsilon_{amp} \times k \times d^2 \qquad (1)$$

**Receiving energy consumption**

$$E_{Rx}(k) = E_{elec} \times k \qquad (2)$$

### 3.4. Self-organization scheme

At first the sink node broadcast an *Invitation* message with the distance parameter $d$ set as r according to Formula (1), and $r$ is the send and receive ranges of each sensor node in the interested field. All the sensor nodes that have received the *Invitation* message will belong to Level n+1, given sink node at Level n+2 as in **Figure 3**, that are also the sink's neighbours. In turn, every sensor node(we call it as holon ) belonged to level n+1 will also broadcast an *Invitation* message with the distance parameter $d$ set as $r$, therefore, if the sensors nodes at level n+1 are in the range of a circle the center of which is the holon broadcasting the *Invitation* message, then they are also the neighbour of this holon. However, If all the holons broadcast *Invitation* message simultaneously, a strange phenomenon will happen, that is, some sensor nodes will belong to the neighbours of different holons at level n+1, we call these sensor nodes as *multi-part*. As in Figure 4, If sensor 1, 2 and 3 at level n+1 broadcast an *Invitation* message at the same time, then the area will be divided into seven regions(i.e., A, B, C, D, E, F, G). If the sensor nodes are in the regions E, F, G, they will only belong to the neighbours of sensor 1, sensor 2 and sensor 3 respectively, and we call these sensor nodes as *part*. However, the sensors in regions B, C, D, will belong to the neighbours of two holons, and the sensors in regions A will belong to the neighbours of three holons(that is, sensor 1, sensor 2, sensor 3) at one time. How to organize the sub-clusters, we correspond to the following rules, and we call these as "Set dividing rule": (1) All the sensor nodes in region E, F, and G only belong to the neighbours of one sensor. For example. the sensor nodes in region E only belong to the neighbours of sensor 1 as in Figure 5. (2) If the number of sensor nodes in region E, F, or G is bigger than a threshold(i.e. $\lambda$ ), only are $\lambda$ sensor nodes selected randomly as the *Member* in the set of neighbours, the rest of sensor nodes in these regions will be in the state of *Stand alone*, Otherwise, the set of neighbours the number of which is smallest has the priority to select the sensor nodes in the region B, C, or D, and even region A as its members, The order of selecting regions is region B, C, or D, next is region A. we call the sensor nodes selected as a member in neighbour set in the state of *Member*. (3) After some time of running in WSNs, some sensor nodes in the set of neighbours will fail for the energy consumption or some other reasons(i.e., weather, temperature, humidity, interference, or obstructions, etc.), Then the sensor nodes in the state of *Stand alone* will be selected as the *Member* in the set of neighbours. The order of selecting regions in this process is region E, F, or G, and then B, C, or D, and the last is region A. For example in Figure 5, if the number of sensor nodes in set of neighbours for sensor 1 is smaller than the threshold $\lambda$, it will first select the sensor nodes in region E which are in the state of *Stand* alone as its *Member* of neighbours. If the number of *Member* in set of its neighbours could not meet the threshold $\lambda$ up to now, it will select the sensor nodes in region B or D which are in the state of *Stand* alone as its *Member* of neighbours again. In turn, the last selected region is region A.

Now we have build up a cluster construct(i.e., cluster 1) between level n+1 and n+2 as in Figure 3 which is an instantiation of holon. Clearly, the neighbour relationship in cluster1 is that Set 1, 2, and 3 are all the sink node's neighbour , but there is no neighbour relationship among Set 1, 2, and 3. Thus it can be seen that "Set dividing rule" is to deal with how to divide different set of neighbours in a cluster at a same level.

Afterwards, we will simply descript how to build up cluster construct at level n and n+1 as in Figure 3. At first all the sensor nodes at level n+1 broadcast an *Invitation* message, the sensor nodes that have received the message but not belong to level n+1 and n+2 will belong to level n. At the same time we have build up different clusters between level n and n+1 based on whether or not receiving the *Invitation* message . Of course, a strange phenomenon will happens that some sensor nodes will belong to different clusters, that is, there is an interaction between different clusters. How to make a decision between sensor node as part, multi-part and different clusters, we correspond to "cluster dividing rule", which is the same with "Set dividing rule" above. Although the sensor nodes playing *Member* role during building up clusters, they also have the chance to change their roles from *Member* to *Stand alone* during building up sub-clusters or sets according to "Set dividing rule".As in Figure 3 we could build up cluster 2 construct at level n and n+1 according to "cluster dividing rule". Clearly, the sensor nodes in cluster 2 composed of Set 4, 5, and 6 are all the neighbours of only one sensor node at level n+1, we call this sensor node as head in a cluster. But there is no neighbour relationship between the rest sensor nodes at level n+1 and the sensor nodes in Set 4, 5, and 6. According to "Set dividing rule", there is no neighbour relationship among the sensor nodes in Set 4, 5, and 6 either. Thus it can be seen that "Cluster dividing rule" is to deal with how to divide different clusters between different levels. The rest may be deduced by analogy, we could build up an extension holonic structure at leve n-1, n-2 , …… until level 1 in WSNs as in Figure 3.

### 3.5. Member model of holon

As in Figure 3, a holon is a conceptual description of cluster which is the instantiation of a holon contrarily. Therefore, a holon is composed of many sub-clusters, that is, there is only one head but many sets in a holon. However, a sub-cluster is only made up of one head and one set. The sensor nodes in a set are in the coequal position which are managed by its head and communicate with each other directly. Nevertheless, the sensor nodes in different sub-clusters only communicate indirectly with the help of its head as a coordinator. Because the sensor nodes in the same set could communicate directly, therefore, the heads at higher level could collaborate with each other that will provide a chance to implement indirect communication between different clusters.

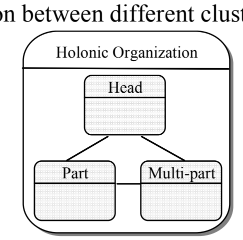


**Figure 6 RIO diagram of the roles played by Sensor nodes in dynamic state**

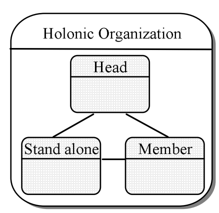


**Figure 7 RIO diagram of the roles played by Sensor nodes in steady state**

During the period of establishing a cluster or sub-cluster, all the sensor nodes are divided into two types based on whether receiving or not, only one or more *Invitation* message, one is *part*, the other is *multi-part* as in Figure 6. We consider that WSNs are now in dynamic state during these time. *Part* means that a sensor node only belongs to one set of neighbours. However, *multi-part* means that a sensor node belongs to more than one sets of neighbours, that is, there is a intersection among different sets of neighbours. As in Figure 3, when WSNs are in the dynamic state, only play the sensor nodes in region E, F, and G the role of *part*, whereas the sensor nodes in region A, B, C, and D play the *multi-part* role.

After implementing the scheme of "Set dividing rule"(or "Cluster dividing rule"), the sensor nodes in a cluster or sub-cluster are divided into another two types, one is *Stand alone*, the other is *Member* as in Figure 7. *Stand alone* means that the sensor nodes are now in the state of inactive, which will be awaken by its head, whereas *Member* means that the sensor nodes are now in the state of active. In order to describe simple, we consider that WSNs are now in steady state during these time. As in Figure 3, when WSNs are in the steady state, the sensor nodes in all regions(i.e., A, B, C, D, E, F, G) have the chance to play either *Stand alone* role or *Member* role, which lies on the threshold $\lambda$.

## 4. Performance analysis

The performance analysis including qualitative and quantitative analysis will be presented in this section.

### 4.1. Qualitative analysis

**4.1.1. Scalability.** As in figure 3, the sensor nodes in the same holon(or cluster) are been managed by its head with decentralized scheme. However, we adopt central architecture between header and sensor nodes which belong to the same holon. This architecture is very useful for deployment of large scale sensor nodes. Therefore, the architecture of WSNs in this paper is applicable to large scale sensor network.

**4.1.2. Distribution.** Obviously, the architecture in this paper adopts distributed sensing data and hierarchically central management scheme in fact, one advantage is scalability as above, the other is to make local decision with local information within a holon or sub-holon, because the sensor nodes in the same set could communicate directly. Furthermore, the sensor nodes belonged to different sets/or sub-cluster could also communicate indirectly with the help of its head. Especially, the sensor nodes in different clusters could communicate indirectly under the coordination among heads at higher level.

**4.1.3. Robustness.** The node near to the sink node has two or three functions as in Figure 1, one is to sense environment, others are to forward data and/or aggregate dat received from other nodes at lower level to sink node. Therefore we could arrive at such a conclusion that the nearer to sink node, the higher load being required compared with the sensor nodes which are far from sink. With time going by, the sensor network will be partitioned into several parts for the energy of some nodes near to sink node having been used up. Researches call this phenomenon as the problem of "hot spot". Since the deployment of sensor node in this paper keeps to the following rule. When WSNs are in its steady state, all the sensor nodes are divided into two types. One is the sensor nodes that play the Stand alone role, the other play the role of Member. When the problem of "hot spot" or partition phenomenon happens, the sensor nodes playing Stand alone role will be awakened from its inactive state to active state, which have the chance to play the Member role.

### 4.2. Quantitative analysis

In this paper, we introduce the *Stand alone* role to implement the property of robustness by prolonging the life time of WSNs, because the sensor nodes playing *Stand alone* role have the chance to be awaken from its inactive state to active state and will be the member of a holon. Therefore in the rest section, we will analyze what will influence the number of sensor nodes playing *Stand alone* role in WSNs.

**Table 1. Terminology**

| Notation | Definitions |
|---|---|
| A | The area of the interested field |
| R | The distance from the farthest sensor node to sink |
| r | The transmission range of sensor nodes |
| $\lambda$ | The threshold of sensor nodes in a set |
| $\chi$ | the threshold of sensor nodes in a holon(cluster) |
| $\xi$ | the number of Sets or sub-cluster in a holon |

Except for using the above deployment model of WSNs in section 3.2, we also introduce another two parameters (i.e., $\chi$ and $\xi$ ). $\chi$ represents the threshold of sensor nodes in a holon(cluster). $\xi$ is defined as the number of Sets or sub-cluster in a holon.Table 1 lists some of the terminologies and notations used in this paper.

According to deployment model of WSNs, N sensor nodes are deployed evenly in a circle region around the centre of sink node. Therefore, we could easily calculate the sensor nodes density(depicted as $\rho_0$ ) in the interested fields as Formula (1).

$$\rho_0 = N/A = N/\pi R^2 \qquad \text{Formula (1)}$$

Without loss of generality, in next we will calculate the sensor nodes playing *Stand alone* role at level n+2-i-1, given sink node at level n+2. According to the deployment model of WSNs and terminologies and notations in Table 1, we could calculate the number of sensor nodes at level n+2-i is as following Formula (2).

$$\begin{aligned} SUM(n+2-i) &= \pi\rho_0\left[(ir)^2-(i-1)^2 r^2\right] \\ &= \pi\rho_0 r^2(2i-1) \qquad \text{Formula (2)} \end{aligned}$$

According to self-organization scheme in section 3.4, the number of cluster is equal to the the number of sensor nodes at level n+2-i. Therefore, we could easily calculate the number of sensor nodes play *Member* role and sensor nodes play *Stand alone* role during building up clusters according to "cluster dividing rule" at level n+2-i-1 as Formula (3) and (4) respectively.

$$SUM_{member(n+2-i-1)} = \pi \rho_0 r^2 (2i-1) \qquad \text{Formula (3)}$$

$$\begin{aligned} SUM_{stand-alone1} &= SUM_{(n+2-i-1)} - SUM_{member(n+2-i-1)} \\ &= \pi \rho_0 r^2 \left[ (2i+1) - \chi(2i-1) \right] \qquad \text{Formula (4)} \end{aligned}$$

Although the sensor nodes playing *Member* role during building up clusters, they also have the chance to change their roles from *Member* to *Stand alone* during building up sub-clusters or sets. Then we could also calculate the number of sensor nodes playing *Stand alone* role according to "Set dividing rule" at level n+2-i-1 as Formula (5).

$$\begin{aligned} SUM_{stand-alone2} &= SUM_{member(n+2-i-1)} - \xi\lambda SUM_{member(n+2-i-1)} \\ &= \pi \rho_0 r^2 \chi (2i-1) - \pi \rho_0 r^2 \xi\lambda (2i-1) \\ &= \pi \rho_0 r^2 (2i-1)(\chi - \xi\lambda) \qquad \text{Formula (5)} \end{aligned}$$

Therefore, when WSNs are in steady state, we can calculate the sum of sensor nodes playing *Stand alone* role at level n+2-i-1 as following Formula (6) according to Formula (4) and (5),

$$\begin{aligned} SUM_{stand-alone} &= SUM_{stand-alone1} + SUM_{stand-alone2} \\ &= {Nr^2}/{R^2} \left[ (2i+1) - \xi\lambda(2i-1) \right] \\ &= O(N)\, O(r^2/R^2)\, O(i)\, O(\xi)\, O(\lambda) \qquad \text{Formula (6)} \end{aligned}$$

According to Formula (6), we can arrive at the conclusion that when WSNs are in steady state, the number of sensor nodes playing *Stand alone* role at level n+2-i-1 is concerned not only with the parameters of N , r, i and R, but also with the parameter of $\xi$ and $\lambda$, which is not concerned with the parameter $\chi$.

## 5. Conclusion

In this paper, we not only propose a RIO model to analyze the roles of sensor nodes in WSNs, but also present a self-organization to construct the holonic architecture in WSNs. Our future researches will focus on some detail technologies, such as data aggregation, coverage optimization based on the holonic model and making a comparison between quantitative analysis and the results achieved through simulation. Especially, we will use the theory of Holonic Multi-Agent Systems and automata theory to formalize the holonic architecture and verify its validation for some properties, i.e., scalability, long lifetime and robustness.

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