J. Electrical Systems 20-7s (2024): 1290-1297

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A Distributed Deployment Method for Wireless Sensor Networks Based on Multi Agent Systems

Journal of Electrical Systems

Abstract: - This paper proposes a distributed deployment method for wireless sensor networks based on multi-agent systems, which addresses the issues of poor self adaptive deployment capability and high deployment costs caused by numerous and diverse types of nodes in the deployment process of wireless sensor networks, leading to blind spots in coverage and redundant nodes. Due to the characteristics of intelligent perception, intelligent communication, and clustering of nodes in wireless sensor network, sensor nodes can be seen as sensing agents, and sensor networks can be seen as distributed multi-agent systems composed of numerous sensing agents. Through the sensing agents' perception of the surrounding environment and communication interaction, a unified deployment model and distributed deployment algorithm with multiple nodes (cluster head nodes) as leaders are established, achieving effective integration of autonomous and leadership mechanisms, distributed management, and centralized management. Taking the problem of sensor network coverage as an example, simulation experiments were conducted, including 12 sensor agents and 1 20 * 20 monitoring areas, to verify how the sensor agents perceive the environment and optimize the migration and deployment process under the coordination of cluster head nodes. The experimental results confirmed the effectiveness of the above models and algorithms. The research results provide a theoretical model and practical approach for the distributed deployment and scheduling of sensor nodes in wireless sensor networks, and can be extended to intelligent Internet of Things systems, such as urban intelligent agent systems, logistics intelligent agent systems, etc., to improve the intelligence of wireless sensor networks deployment and scheduling.

Keywords: Multi agent systems; Wireless sensor network; Distributed deployment

I. INTRODUCTION

Wireless Sensor Network (WSN) is a distributed sensor network system composed of multiple nodes with sensing and communication functions, which has clustering and hierarchical characteristics. As shown in Fig. 1, it is a two-dimensional network with three layers. The bottom layer consists of sensor nodes distributed in the target area, with several clusters, each with a cluster head (aggregation node). These cluster heads form an intermediate layer, and each sensor node can directly communicate with their cluster head. The cluster head can communicate with the top layer's *Sink* node (management node).

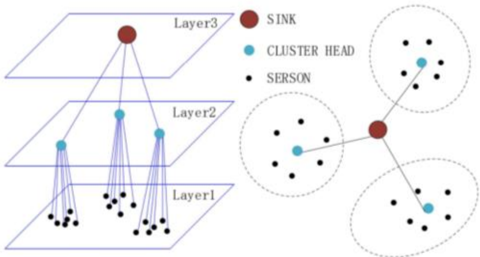

Fig. 1The network architecture diagram of WSN

With the deepening development of new generation information technologies such as artificial intelligence and cloud computing, research on WSN has gradually penetrated into various fields, such as path scheduling, target tracking, disaster warning, and wearable devices [1]. Among them, the deployment coverage of WSN is a key issue and also one of the difficulties. The size of coverage reflects the performance and efficiency of WSN. In traditional WSN, the deployment location of sensors is mostly determined by random scattering. The network deployed through this method is prone to uneven node distribution, resulting in high node density in some space, which leads to a decrease in network coverage, sensor speed, and efficiency. To solve this problem, it is necessary to optimize the node deployment method. Currently, scholars have conducted extensive research on the integration of swarm intelligence optimization algorithms and WSN deployment optimization. For example, MIAO et al. [2] applied the grey wolf optimization algorithm to enhance the hierarchical structure, while DEEPA et al. [3] proposed the whale optimization algorithm using Levy flight enhancement and applied it to WSN coverage optimization. Song Mingzhi et al. [4] proposed an improved virtual force ion swarm algorithm and applied it to the random deployment of WSN

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nodes. DEB et al. [5] combined the TLBO algorithm [6] with the CSO algorithm [7] and proposed a chicken swarm optimization algorithm based on teaching and learning algorithms for deployment optimization of WSN nodes.

Random scattering leads to blind deployment of WSN, resulting in high optimization costs in the later stage. If sensor nodes with communication perception ability are regarded as intelligent agents, then WSN can be seen as a distributed multi-agent system composed of multiple local sensor networks. Applying the autonomous decision-making and centralized management of distributed multi-agent systems to the deployment of WSN is a valuable research direction. At present, research on multi-agent systems mainly focuses on areas such as multi-agent reinforcement learning, multi-agent communication, distributed decision-making and collaboration, path planning and collaboration, collective behavior, and social agents [8]. The study of distributed consistency and collaboration among multi-agent systems involves studying how agents achieve consistency and cooperation in distributed environments, involving distributed algorithms, protocols, and how to enable agents to complete tasks together without central control [9-10]. Multi agent path planning and motion collaboration, focusing on path planning, obstacle avoidance, and collaborative motion of multiple agents in a shared environment. The progress includes effective path planning algorithms and motion coordination strategies in dynamic environments [11]. Multi agent distributed decision-making and negotiation, studying how to enable multi-agent systems to negotiate, coordinate, and reach consensus during the decision-making process, involves game theory, contract theory, etc. [12-13]. Multi agent communication studies the communication methods between intelligent agents, including information transmission, sharing, and encoding, including adaptive communication strategies, network topology design, etc. [14-15]. The collective behavior and collective intelligence of multi-agent systems, studying the behavior of intelligent agent groups, exploring how collective behavior arises from local interactions, involving behavior models in nature such as bird and fish schools, and how to apply them to technical systems [16]. Social agents are intelligent agents that simulate human social behavior and emotions. Progress in this area includes emotional modeling, social norms, and collaboration between humans and robots [17].

The above research on multi-agent systems, such as distributed decision-making and central control, has strong inspirational significance for the deployment of WSN. The clustering and hierarchical communication mechanism of WSN provides a natural organizational approach for distributed decision-making and cooperation in sensor networks. Based on the clustering characteristics of WSN, a unitization idea of WSN is proposed, which divides large-scale WSN into units according to themes or regions, forming a globally distributed WSN composed of several local cluster networks. Distributed management of WSN's clustering network, with local coordination by cluster head nodes and communication between Sink nodes and cluster head nodes, to achieve overall coordination and control of the global WSN. We have constructed a three-level communication mechanism consisting of ordinary nodes, cluster head nodes, and sink nodes, as well as a centralized command and coordination mechanism led by cluster head nodes and Sink nodes, to promote the effective unity of distributed management and centralized management. The main research content of this article is as follows:

(1) Based on the cluster characteristics of nodes in WSN, establish a WSN cluster model and a distributed WSN model.

(2) Established a distributed communication and centralized coordination model for WSN.

(3) Designed a distributed deployment algorithm for WSN.

II. A Distributed Deployment Method for WSN

A. *Distributed WSN Model*

Convention: $S=(N,E)$ is a wireless sensor network, $N=\{n_1,n_2,\cdots,n_n\}$ is the collection of sensor nodes in S, $E=\{e_1,e_2,\cdots,e_m\}$ is a collection of connections in S, $j(n_i,n_j)$ is the number of hops between n_i and n_j, and $d(n)$ is the degrees of n(the number of edges connected to n).

Definition 1: The Cluster Model of WSN

Let $S'=(N',E')$ be a subnetwork of $S=(N,E)$, $N'\in N,E'\in E$, If there is a node $n\in N'$, such that any other node n' in S', satisfies: $J(n,n')=1$, It is called a cluster network in *S* with *n* as cluster head, denoted as:

$$C(n,n')=C(S'|S,n,n') \qquad (1)$$

In Eq. (1), n is the cluster head of S' and n' is the sensor node of S'

Definition 2: Distributed WSN model

Let $C_1(n_1,n_1')$, $C_2(n_2,n_2')$,..., $C_m(n_m,n_m')$ be a cluster of $S=(N,E)$ respectively, satisfies: $S=C_1\cup C_2\cup\cdots\cup C_m$ and $C_1\cap C_2=\Phi$, $i,j=1,2,\cdots m,i\neq j$, $C_1,C_2,\cdots C_m$ form a distributed WSN of *S*, denoted as:

$$D\{S|C_1, C_2, \cdots C_m\} \quad (2)$$

Definition 3: Distributed WSN Communication Model

Let $D\{S|C_1, C_2, \cdots C_m\}$ be a Distributed WSN, $C_1(n_1, n_1')$, $C_2(n_2, n_2')$,…, $C_m(n_m, n_m')$ be a cluster of $S = (N, E)$, respectively, $i = 1,2, \dots, m$, If there exists a node s, such that $j(s, n_i) = 1$, then s is called a *sink* node (management node) in a distributed WSN. It is called the communication model of distributed WSN, denoted as:

$$D\{S|C_i(n_i' \rightarrow n_i \rightarrow s), i = 1,2, \dots, m\} \quad (3)$$

Distributed WSN has the property of hierarchical communication. During the communication process, the sensor node communicates with its cluster head node, and the cluster head node interacts with the sink node.

Definition 1-3 is shown in Fig. 2.

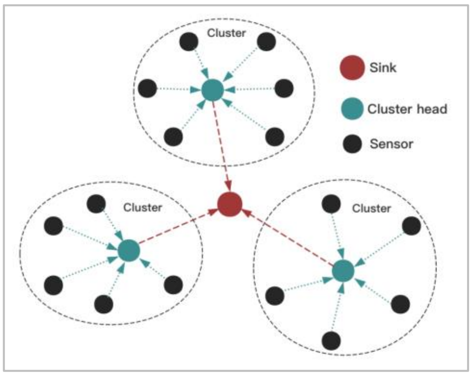

Fig. 2 Schematic diagram of distributed WSN and its communication mechanism

B. *The Distributed Deployment Model of Model*

Set detection area A, where point p is any point on A. The goal of distributed WSN deployment is to ensure that any point p on A can be detected by at least one sensor node in the distributed WSN, that is, to ensure that the deployment of WSN nodes has the maximum coverage.

Let $D\{S|C_1, C_2, \cdots C_m\}$ be a Distributed WSN, $A(C_i)$ is the effective perceptual detection area of the cluster C_i in WSN, where $i = 1,2, \dots, m$. Then the effective perceptual detection area of WSN is:

$$A_S = \text{Max}\left(\sum_{i=1}^{m} A(C_i)\right) \quad (4)$$

In order to achieve maximum coverage in WSN, it is necessary to minimize the overlap of detection regions between each cluster, namely:

$$\text{Min}\left(A(C_i) \cap A(C_j)\right) \quad (5)$$

In Eq. (5)， $i, j = 1,2, \dots, m, i \neq j$.

In order to achieve maximum coverage for WSN, it is necessary to achieve maximum coverage for each cluster, namely:

$$A_{C_i} = Max\left(\sum_{j=1}^{l} A(n_{ij}')\right) \quad (6)$$

In Eq. (6), $A(n_{ij}')$ represents the coverage range of sensor nodes in C_i.

In order to achieve maximum coverage for each cluster, it is necessary to minimize the overlap of detection areas among sensor nodes within the cluster, namely:

$$Min\left(A(n_{im}') \cap A(n_{in}')\right) \quad (7)$$

In Eq. (7), $m, n = 1,2, \dots, l, m \neq n$.

In the deployment of distributed WSN, to ensure the maximum effective coverage area, it is necessary to ensure that the overlap of coverage area of each node and each cluster is minimized, while ensuring that the nodes are within the effective communication range. The deployment model is shown in Fig. 3, with the smallest overlap area between nodes and clusters within each cluster $C1$, $C2$, and $C3$.

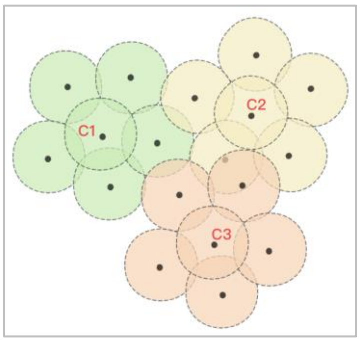

Fig. 3 Schematic diagram of the deployment model for distributed WSN

III. Deployment Algorithm for Distributed WSN

A. The Deployment Strategy of Distributed WSN

Cluster a large-scale WSN to form a distributed WSN. The basic idea is as follows: Based on the size of the detection area to be perceived and the scale of the WSN, the WSN is clustered, with each cluster corresponding to a detection area, which can ensure the uniformity of region detection coverage. The deployment of each cluster adopts heuristic deployment methods to avoid blind deployment. After each cluster deployment is completed, according to the optimal coverage principle, optimize the deployment of each cluster first to ensure that the coverage of each cluster is optimal; Then, perform overall coordination on all cluster coverage to achieve global optimization. Its deployment strategy is shown in Fig. 4.

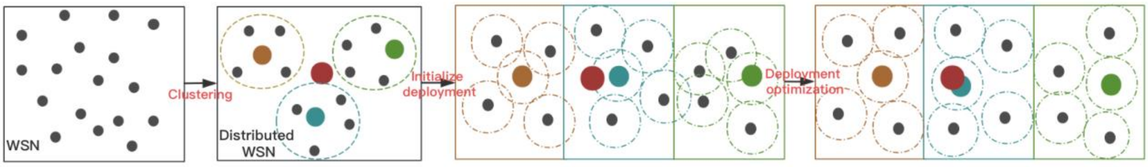

Fig. 4 Schematic diagram of WSN deployment strategy

B. Units Deployment Algorithm for Distributed WSN

1) Cluster Algorithm for WSN

Based on the situation of the area to be detected, including the shape and size of the area, as well as the scale of the WSN, the WSN is divided into clusters. The basic steps are as follows:

(1) Determine the number of WSN clusters;

(2) Divide nodes into different clusters according to their labels;

(3) According to the principle of minimum labeling, select the node with the smallest label in each cluster as the cluster head node;

(4) According to the principle of minimum labeling, the node with the smallest label in the cluster head node is elected as the Sink node.

Algorithm-1：Cluster algorithm for WSN

Input：$S = (N, E)$

Output：$D\{S|C_1, C_2, \cdots C_m\}$

Process:

01: Initializing number of clusters for WSN: $C_1, C_2, \cdots C_m$

02: Partitioning the nodes of $S = (N, E)$ to $C_1, C_2, \cdots C_m$ in order of the labels of nodes

03: Selecting the node with the smallest label for $C_1, C_2, \cdots C_m$ as the cluster head node

04: return $C_1(n_1, n_1'), C_2(n_2, n_2'), \ldots, C_m(n_m, n_m')$

05: Selecting the node with the smallest label from all cluster head nodes of $C_1, C_2, \cdots C_m$ as the *sink* node

06: return $D\{S|C_1, C_2, \cdots C_m\}$

2) *Distributed Deployment Algorithm for WSN*

The basic process of distributed deployment of WSN is as follows:

(1) Pre allocate each cluster to the designated monitoring area.

(2) In each detection area, a heuristic method with cluster head nodes as the core is adopted to deploy nodes within the cluster to the detection area.

(3) Optimize the deployment nodes for each detection area based on the principle of minimizing the overlap of monitoring ranges between nodes, ensuring that the monitoring coverage of each node is maximized in each detection area.

(4) For all areas to be detected, optimize according to the principle of minimizing the overlap of monitoring ranges for each cluster in WSN, to maximize the monitoring range of the entire WSN.

Its algorithm is shown in Algorithm-2.

Algorithm-2：Distributed Deployment Algorithm for WSN

Input： Area to be monitored：$A_1, A_2, \ldots, A_m, D\{S|C_1, C_2, \cdots C_m\}$

Output： $A(C_1), A(C_2), \cdots, A(C_m)$

Process:

Assigning $C_1, C_2, \cdots C_m$ to $A_1, A_2, \ldots, A_m$, separately
for each $C \in [C_1, C_2, \cdots C_m]$, each $A \in [A_1, A_2, \ldots, A_m]$ do
    Initializing nodes of C to A
    return $A(C)$
end for
for each $A(C) \in [A(C_1), A(C_2), \cdots, A(C_m)]$ do
    for n_i, n_j in $A(C)$ do
        Adjust the position of n_i, n_j in $A(C)$ to satisfy: $Min(A(n_i) \cap A(n_j))$
    end for
end for
for each $A(C_i), A(C_j) \in [A(C_1), A(C_2), \cdots, A(C_m)]$ do
    Adjust the position of $A(C_i), A(C_j)$ to satisfy: Min $(A(C_i) \cap A(C_j))$
end for
return $A(C_1), A(C_2), \cdots, A(C_m)$

IV. EXPERIMENT

A. *Description of Experimental Environment*

The experimental environment includes a 20 * 20 monitoring area and a wireless sensor network consisting of 12 sensors, with an effective sensing radius of 2. As shown in Fig. 5.

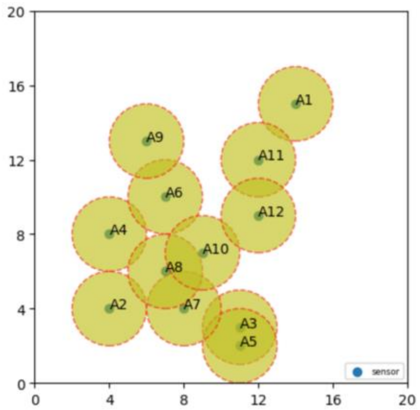

Fig. 5 Experimental Environment for WSN Distributed Deployment

The experimental objective is to deploy WSN to the monitored area based on the ideas of distributed decision-making and centralized coordination in the above models and algorithms, in order to achieve the optimal coverage target.

B. *Experimental* Process

1) *The Formation of Distributed WSN and Its Heuristic Deployment*

Divide the WSN into clusters based on the area to be detected and the size of the WSN, forming a distributed WSN. Divide the detection area based on the number of clusters divided. Using cluster head nodes as the core, heuristic deployment is performed on each cluster in each detection area, as shown in Fig. 6. The position coordinates of WSN sensor nodes in the area to be detected are shown in Tab. 1.

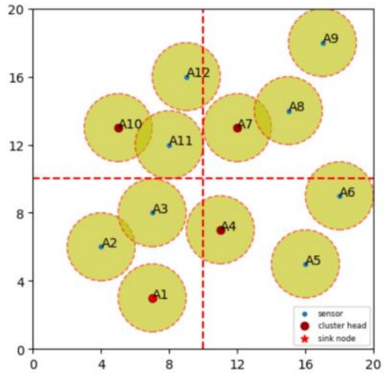

Fig. 6 Initial deployment diagram of WSN

Tab. 1 Cluster partitioning and initial deployment of WSN

Cluster id	The coordinates of the nodes in each cluster	Cluster head	Sink node
1	A1(7,3), A2(4,6), A3(7,8)	A1(7,3)	A1(7,3)
2	A4(11,7), A5(16,5), A6(18,9)	A4(11,7)	A1(2,3)
3	A7(12,13), A8(15,14), A9(17,13)	A7(12,13)	A1(2,3)
4	A10(5,13), A11(8,12), A12(9,16)	A10(5,13)	A1(2,3)

2) *Deployment Optimization of Distributed WSN*

According to Algorithm 2, first, according to the principle of minimizing node overlap within the cluster, cluster head nodes coordinate to optimize the deployment of the cluster itself; After the intra cluster optimization is completed, the WSN's management nodes coordinate to perform overall optimization. During the deployment optimization process, the sensor nodes within the cluster send location information to the cluster head node, which calculates and coordinates the information. Then, the deployment information is fed back to the sensor node, which adjusts its position on its own, as shown in Fig. 7; After the optimization of intra cluster node deployment is completed, the cluster head node feedbacks the intra cluster deployment situation to the management node, which coordinates. The inter cluster adjustment and optimization process is shown in Fig. 8.

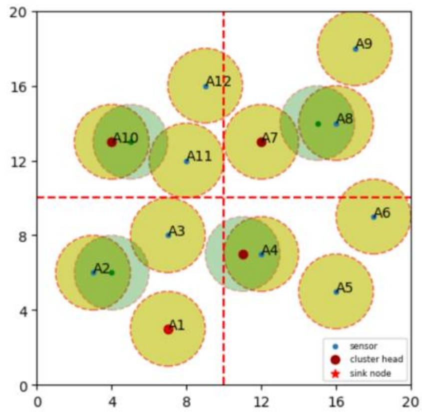

Fig. 7 Deployment optimization of clusters themselves of WSN

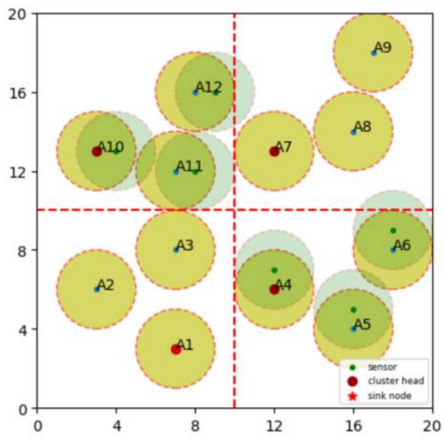

Fig. 8 Global deployment optimization of WSN

The optimized deployment coordinates of WSN are shown in Tab. 2.

Tab. 2 Optimized deployment coordinates of WSN

Cluster id	The coordinates of the nodes in each cluster	Cluster head	Sink node
1	A1(7,3), A2(3,6), A3(7,8)	A1(7,3)	A1(7,3)
2	A4(12,6), A5(16,4), A6(18,8)	A4(12,6)	A1(7,3)
3	A7(12,13), A8(16,14), A9(17,18)	A7(12,13)	A1(7,3)
4	A10(3,13), A11(7,12), A12(8,16)	A10(3,13)	A1(7,3)

C. *Analysis of Experimental Results*

From the experimental results, it can be seen that the distributed deployment of WSN can ensure that it is located in the respective areas to be monitored. Although the node distribution tends to be centralized, it is roughly balanced within the interval, providing a basis for subsequent adjustment and optimization; During the adjustment and optimization process, minor adjustments were made within the cluster, only adjusting the positions of A2, A4, A8, and A10; Inter cluster deployment optimization only occurs between two clusters, with small adjustments and minimal overall deployment optimization costs. Through the distributed deployment and centralized coordination of WSN, effective unity of distributed autonomous decision-making and centralized unified command can be achieved, improving overall deployment efficiency.

V. CONCLUSION AND OUTLOOK

The combination of multi-agent systems and WSN is a way to promote the development of AIOT. This article integrates wireless sensor networks with distributed multi-agent systems and establishes a distributed WSN model. Based on the intelligent perception and communication capabilities of sensor nodes, utilizing the autonomous decision-making ability of sensor agents and the centralized command ability of cluster head nodes in distributed WSN not only fully stimulates the autonomy of agents, but also avoids the blind and disorderly state in traditional random deployment mode, achieving effective unity of autonomous management and centralized management, autonomous mechanism and leadership mechanism, distributed management and centralized management. The research results can be extended to intelligent IoT application scenarios such as urban intelligent agents, transportation intelligent agents, and logistics intelligent agents, leveraging the distributed intelligence in large-scale IoT systems and achieving effective centralization under distributed management. But how to achieve sufficient state awareness and information exchange in WSN, and achieve complete autonomy under centralized leadership, is the direction for WSN to achieve intelligence. On this basis, combined with the communication mechanism of multi-agent and graph network theory, further research will be conducted on the intelligent perception, intelligent communication, intelligent cooperation, and intelligent decision-making of the intelligent Internet of Things, promoting the further development of the intelligent Internet of Things.

ACKNOWLEDGMENT

This research is supported by Digital Fujian Industrial Energy Big Data Research Institute (Grant No. KB180045), Key Laboratory of Industrial Big Data Analysis and Application in Fujian Universities (Grant No. KB180029), Exploration and practice of the construction of ICT industry colleges based on new engineering disciplines(Grant No. JA22091P).

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