Game Theoretical Algorithm for Coverage Optimization in Wireless Sensor Networks

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***Abstract*—Game Theory is fundamentally and applicably addressed and incorporated to analyze the coverage problems in Wireless Sensor Networks (WSN) in this paper. GCC (Game-theoretical Complete Coverage) algorithm is used to ensure whole network coverage mainly through adjusting the covering range of nodes and controlling the network redundancy. Hereafter, by designing suitable cost and utility function for each nodes, simulations prove the efficiency and applicability of GCC algorithm and also inspire that GCC is an excellent way for time scheduling and keeping Network Integrity.**

***Index Terms*—Network Integrity, Topology Control, Game Theory, Wireless Sensor Networks**

I. INTRODUCTION

With the rapid development of wireless communication technique, embedded technique, sensor technique, researchers try to deal with some new techniques and range of applications which are differ from traditional means. Although sensor is one method during people apperceive physical world, individual sensor cannot share information and workload within certain area. Then, scholars and engineers imagine how to connect sensor networks' nodes which are low-power-consumption, low-cost and multifunctional in a certain area. It can make nodes work collaboratively by the communications, data processing, data fusion, self-organization mechanism of collaborative nodes in order to make up drawbacks in technology. Scientists and technicians are paying more and more attention to a new technology which involves SOC (System on Chip) and Ubiquitous Computing. That's "Wireless Sensor Networks" technology.**Error! Reference source not found.** [2]

People have become to concern with whole application of sensors since 1950s, early applications only limit to sensor nodes assemble "system". There were real sensor "networks" for the appearance of Bitbus[1][3]between the late 1970s and the early 1980s. Nowadays, game theory has been employed in Wireless Sensor Networks quite extensively nowadays. Many interesting results have been reported in the literature.

Game theory is a branch of applied mathematics. Its fundamental assumption is that players go after some certain aim and forecast other players' actions by their knowledge. Most applications of game theory involve in the areas of decision making, management, economics and finance. However, a few scholars and researchers began to pay attention to the application of game theory in Wireless Sensor Networks recently.[4]

We solved the self-organization problem of networks after using the game theory in WSN because the nodes are cognitive and can make decision intelligently. The communication in WSN is helpful to extend the application scopes, to heighten the effects of resource utilization, to save unnecessary waste. In multi-node communication networks of this kind, there are two opposite phenomena cooperation and competition.

There's competition for resource limitation; there's cooperation for the network scalability requirements. Nodes are intelligent and restricted by definite protocols in this kind of networks. On the premise of mission completion, we can follow the rules of utility function to make each node organize and distribute by itself. It achieves effective and reasonable control for routing, energy, topology, network integrity after applying game theory.[5]-[14]

II. Game Theory and Wireless Sensor Networks

A. Game Theory [18][19]

A fundamental game process includes the following:

1) Each network will be a set of nodes if the network N is consisted of nodes, and the number of nodes is k, namely that $N = \{n \in i, i = 1,2,...,k\}$

2) Each node has respective working pattern in its own working process. According to the difference between management modes of node micro-embedded operating system and scheduling modes of whole network, each node has its own power control strategy and energy consumption property. Suppose each node has m kind of scheduling strategy, energy strategy of each node in different scheduling modes is $p_i^{\,j}$, then energy strategy space P_i is the Cartesian product of $p_i^{\,j}$.

$$\forall n_i \in N, i \in \Gamma, P_i = \{p_i^1 \times p_i^2 \times ... \times p_i^j \times ... \times p_i^m, 0 \le j \le m\}$$

3) Through collect, send, and receive information, each node which works in the network is able to play its given function and acquire definite payoff in its specific operating state. Which is expressed as

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[1] Bitbus is one kind of Serial vs Parallel Bus Structures designed for communication transmission in distributed control system by Intel.

$$\pi_i(p_i^1, p_i^2, ...p_i^m), \forall n_i \in N, i = 1, 2, ..., k$$

Usually, π_i is called as the Payoff of player i.

On this, we consider p_i^* is the dominant strategy of node i, which is

$$p_i^* \succ p_i^{'} \Leftrightarrow \pi_i(p_i^*, p_{-i}) > \pi_i(p_i^{'}, p_{-i}), \forall s_{-i}, \forall s_i^{'} \neq s_i^*$$

here, $p_{-i} = (p_1, p_2, ...p_{i-1}, p_{i+1}, ...p_m)$, $\succ \equiv \{\succ^i_{(p_i^*, p_i^{'})} : i \in \Gamma, p_i^* \in P_i, p_i^{'} \in P_i\}$.

4) Nash Equilibrium

Nash equilibrium is that neither player has a unilateral incentive to change its strategy. Suppose to all nodes the whole game is

$$G = \{P_1, P_2, ...P_k, \pi_1, \pi_2, ..., \pi_k\},$$

Strategy combination $p^* = (p_1^*, p_2^*, ..., p_m^*)$ is Nash equilibrium. In another word, p^* is the solution of the problem which as follow

$$p_i^* = \arg\max_{p_i^* \in P} \pi_i(p_1^*, p_2^*, ...p_{i-1}^*, p_i, p_{i+1}^*, ...p_m^*), i = 1, 2, ...m$$

5) Pareto efficiency

A strategy profile is Pareto optimal if some players must be hurt in order to improve the payoff of other players.

Def: A strategy profile s^* is said to be Pareto optimal if there exists no other strategy profile s', such that

If for some j

$$u_j(s') > u_j(s^*), u_i(s') > u_i(s^*), \forall i \in I \setminus j$$

That's to say, Pareto efficiency is a situation in which every way to change the resource distribution will not improve the payoff of any node if there's no hurt to other nodes. Pareto efficiency means the maximal efficiency of the resource distribution. Any other solution all reduces the efficiency. In this case, no nodes will change their strategy to optimize network structure actively.

B. Game Theory for Wireless Sensor Networks

1, Nodes Classification

Usually, nodes in the research of game theory for WSN are classified for two classes.[2]

Honest Nodes

Nodes choose cooperation with other nodes directly in order to complete information transmission. These nodes are called as honest nodes.

Cheating Nodes

Nodes choose to cheat or use network resources rather than complete information transmission. These nodes are called as cheating nodes. These nodes are selfish. However, they intend no harm. They can cooperate with other nodes or have their full swing.

The classification can be applied to manage network resources directly. Then, nodes play games; make self decision and self-organization within the network.

2, Interference Avoidance Methods

Apply game theory to interference avoidance model to achieve the reliability and validity of network information transmission. Another essential aim is to minimize the interference between nodes and maximize the rational use of energy.

3, Power Management

(1)Apply the one-stage game and repeated game to power management models, and power control of network nodes, punishment strategy, nodes and network power efficiency will be discussed.

In each process of game, sink node provides energy level data and broadcasts the data to his neighbor sink node. We confirm an energy level through the Nash Equilibrium of single-stage firstly. If energy of a node departs from its strategy energy, other nodes will increase their energy levels in order to realize the punishment of the node. In this case, all the nodes can know other nodes' energy condition; in every stage of game, the energy distribution of every node achieves equilibrium; during the whole repeated game processes, realize gradually certain equilibrium which is more effective than single-stage Nash Equilibrium.

(2)Then, we will apply the Joint-Strategy Fictitious Play[3][20] to energy control model, and discuss the power control of nodes in the network to achieve the validity of nodes and networks.

The basic assumption of Joint-Strategy Fictitious Play is to get a certain discreet value by doing the dynamic experiment which changed the topology frame. In this changing process, the aim of changing network topology is to advance the history behavior of nodes' network, to find an optimal prior estimate. Joint-Strategy Fictitious Play is progressive study arithmetic. It has study ability in the changing process.

The object node considers all the other nodes' behavior, and decides optimal response. Conceptually, the model applied from the effective energy control of Joint-Strategy Fictitious Play needs check neighbor nodes' coordinate in the area. The check aim is to affirm whether the node is covered.

4, Congestion Control

The congestion will occur when there are more data packages than peak load. At that time, nodes in WSN will distribute network resources intelligently, restrict packages' speed and flow, and carry congestion control according to their own payoff.

5, Mobile Sensors' Management

Mobile sensors' resources provide free and dynamic sustain for strategy, especially for space environment factor. We suppose system is mainly controlled by its consisting member. If parts of member fail, such as node dormancy or failure, these nodes will degrade themselves properly to assure the robustness and integrity of networks. This action is called Decentralized Control.

III. GAME-THEORETICAL COMPLETE COVERAGE ALGORITHM

In WSN, network topology control is one of the important techniques, and the network coverage problem is the most important problem in this area, it is also the fundamental factor in the network integrity. It is a valuable topic that how

[2] Professor Jorma Virtamo in the speech "Applications of Game Theory in Ad Hoc Networks".

3 Joint Strategy Fictitious Play (JSFP) is a close variant of FP, accommodates information aggregation and gets a better strategy.

to set every sensor nodes' inductive area effectively until the area is covered completely. Error! Reference source not found.[5][22]

It has been limited in the research for complete coverage until now. Consequently, effective and rapid complete coverage arithmetic is very few. Firstly we consider using fixed value as every node's inductive coverage area. Then, we will find great waste in the compatible problem for coverage area's multi-purpose. So, we should give an inductive area which is dependent of energy cover area. This area indicates the bound of detection in order to advance the efficiency and to save energy.

In such background, this paper gives a new arithmetic to solve the complete coverage problem. It is the Game-Theoretical Complete Coverage (GCC) arithmetic. This arithmetic decides a proper cover area in a new network through dynamic game process.

A. Problem description

In a topology changed network, parts of nodes' energy cover area should be decided again. Mobile and sleeping nodes will make topology changed. In this case, every node maybe is facing with a new choice. [5][13]

In most cases, the way to solve this problem is to design nodes conformably in the beginning of designing networks. We can through the early networks' topology optimize a relatively good plan to set the inductive area of every node. This way is easy to manage and design. However, its disadvantage is also very evident. For some nodes, there are energy dissipations to use the same inductive area; for others, there are some particular areas which can not be covered. This way is feasible in the early application of WSN. However, in network era with rapid changes, it's impossible to meet the demand of the network stability with rapid changes only through early period design. The aim of GCC is to research how to avoid the series of shorts rapidly and effectively.

The research of this paper takes a random network with 50 nodes for instance. Firstly, fix the inductive area to the energy cover area. The actual network status is showed as figure 1. One could see that the network status isn't complete coverage. We use a certain gray scale to represent every node's cover area. There are many deep color areas in the Figure1, which indicates most areas have repeated coverage. Undoubtedly, this method causes great energy dissipations and low coverage efficiency. Because the network is created at random, the data has some randomicity. The following conclusion is got from a certain number of simulation tests.

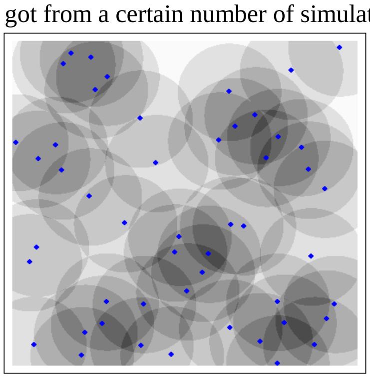

Fig.1The modeling of complete coverage problem

The grey circle in Fig.1is every node's inductive area. Firstly, we use a same energy level to all nodes. It's a casual value and represents nothing. It's only a reference for the basic model of a network. One could see clearly that areas where nodes are dense, coverage area obvious multi-overlap. In this area, there are serious noise jamming and energy dissipation. These overlapping areas can't provide extra payoff, so we should reduce them properly.

B. Algorithmic Description

This paper's aim is to design an arithmetic which can calculate the minimal energy cover area on the premise of complete coverage network. Compared with the arithmetic before, the method can make rational use of energy and expand network coverage. In order to achieve this object, nodes must choose different inductive areas according to different cases.

We must design an intelligent system to all nodes, and nodes use it to decide their inductive area. The intelligent system is realized by the basic theory of game. Firstly, nodes calculate their payoff in every energy level and the whole benefits of network. Then, nodes will choose the maximal payoff and decide their inductive area.

So, we designed a repeated game model. If the whole network is a game, this game will be consisted of three parts.

- A set N of players, nodes are players, which is denoted as i, $i \in N$.
- A set S of strategy, there are three strategy, which is decrease, increase and follow.
- Payoff is a choice set of every player.

During every game, all nodes consider strategy again, action as their choice, and change energy cover area until repeated games finish. The energy coverage area of all nodes in this time is the final solution.

The game process of this model only considers current status rather than history status and actions. So it can be applied to most situations of mobile WSN.

C. Payoff Function Configuration

The most crucial point in this arithmetic is the choosing of payoff. It's same as game. We can find optimal solution after we find payoff. In order to explain the payoff in this paper, we define some terms firstly.

Coverage: Coverage is in the ratio of the actual cover area to required cover area. If complete coverage is required, the coverage is 100%.

Coverage level: the coverage level of any position in WSN equals to the number of nodes in whole network that can cover this node.

Then, payoff of every node in game is defined as follow. Firstly we suppose:

1) The value of complete coverage is 1, which means that to all nodes the most important thing is complete coverage.

2) The value of every node's energy cover area is $-\alpha \cdot r_i^2, i = 1, 2, ..., N$. In this, r_i is the inductive radius of node i; α is an extremely small parameter, $0 < \alpha < 1$, and α decides the value of energy consumption. Smaller energy cover area saves more energy, so there's no doubt that nodes with smaller energy cover areas are preferred. The negative

symbol is used to express this meaning. The larger α is, the more important energy consumption of nodes is and vice versa.

3) The value of every node's inductive area edge location is $\beta \cdot p$. β is also an extremely small parameter, $0 < \beta < 1$, and β decides the importance of coverage level that should be considered during the nodes' decision. β is decided for practice. The larger β is, the more important coverage level is and vice versa. p is the level efficiency of coverage level. We should consider the coverage level of all nodes in the energy circle. If p is decreased in a position with high coverage level, it means that the covered position is not very important so that the whole efficiency decreases. If p is increased in a position with low coverage level, it means that the covered position is relatively important so that the whole efficiency increases. All in all, we will check up every position condition in reality and calculate influence of every position within the circle to p. Then, we can get the final value of p to calculate the final payoff.

4) $\mathbb{U} = \sum_{i=1}^{N} \pi_i$,which means the whole network's payoff equals to the sum of all nodes' payoff. In a word, we can conclude that the payoff is :

$$Payoff = 1 - \alpha \cdot r^2 + \beta \cdot p$$

After find the Payoff, we can complete the arithmetic with it.

D. Algorithmic Flow

The actual arithmetic flow is showed as Fig.2.

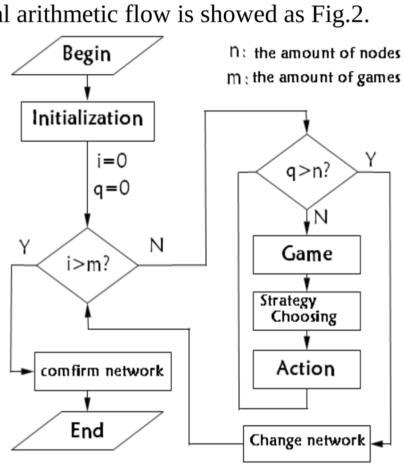

Fig.2 Algorithmic Flow of GCC

In the flow, "Gaming" means to find the payoff in every strategy. "Choosing" means to choose the maximal payoff. "Action" means to change nodes' cover area according to strategy. During repeated games, the whole network achieves Nash Equilibrium. The Nash Equilibrium is the final optimal solution.

E. Arithmetic improved

Although GCC can achieve the aim of complete coverage, we can achieve better solution if we make some change to GCC such as setting some Game strategies. Then let's introduce the essential concepts of the improved arithmetic.

Anticipant Nodes: The nearest node in a position is this position's anticipate node, which means the node with lowest energy level in all nodes.

Payoff isn't changed here, what is changed is the decision-making method. In GCC, the problem every node consider during game is to use the minimal energy and cover neighbor position. In the improved arithmetic, we introduce in a new judgment mechanism, which can decide whether nodes should consider this position or not through anticipant nodes in a position. When a position is out of a node's consideration, although the cover level in this stage is 1, sometimes even is zero, the value of p should be decreased relatively instead of increased. When a position stay in a node's consideration, whatever how high the cover level is, the value of p should be increased instead of decreased.

This way can make the inductive areas of all nodes cover those easy to cover rather than neighbor nodes. Relatively speaking, the improvement of efficiency is obvious. The actual data of efficiency improvement will be calculated detailedly in simulation.

IV. SIMULATION

In order to explain the efficiency of GCC, we design a simulation system to simulate game model. VC++ is used here for simulation. Firstly a rectangular area is created as the WSN bound. Here the size of rectangular is 100m*100m. Then, 100 nodes are distributed randomly in this area. This simulation system is used to create WSN randomly, so all the computing results have definite random factors, Figure3 is an actual computing result.

Fig.3 has the same network frame as Figure1, and Figure3 is the simulation result of GCC. The red nodes in black circles mean the nodes which can sleep briefly now. We can see clearly that many nodes' inductive areas are adjusted to a better value after the repeated game. There're many sleeping nodes and the network coverage comes to 100%.

For there's no authoritative and effective to compare with, we compare the energy consumption of GCC with improved GCC. Fig.4 is the simulation result of improved GCC. We can find that there're more sleeping nodes and the grey scale of the whole area reduce obviously on the premise of complete coverage. We make many analysis and comparison with repeated experiments as follows.

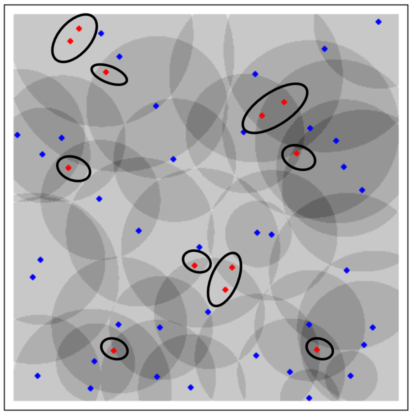

Fig.3 Simulation result of GCC

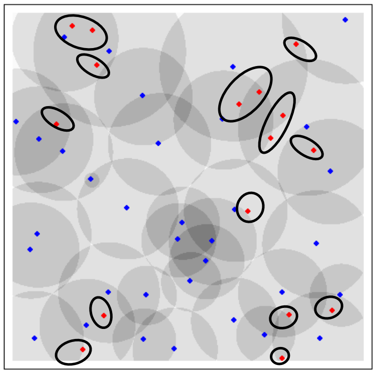

Fig.4 The simulation result of improved GCC

If we create a network with nodes from 10 to 100 randomly and process complete coverage with GCC and improved GCC, we will get Figure5 and Figure 6. Figure5 is the comparison of GCC and Improved GCC; Figure6 is the improved percent chart. We use the definition below to compare the improvement between two algorithms.

$$\text{Optimization percentage} = 1 - \frac{\boldsymbol{Energy}_{improvedGCC}}{\boldsymbol{Energy}_{GCC}} \times 100\%$$

$\boldsymbol{Energy}_{improvedGCC}$ stands for the energy consumption of improved GCC. $\boldsymbol{Energy}_{GCC}$ stands for the energy consumption of GCC.

So, the optimization percent can show the advantage of improved GCC clearly.

Figure6 proved that the optimization percent generally reaches 40%.

Only by changing the payoff, one can change the efficiency of the final game result dramatically. This shows a great prospectus of the appliance of Game Theory in WSN. Upon further researching and payoff to be more true and accurate, percentage of efficiency optimization tends to be close to intellectual perfect basic hypothesis.

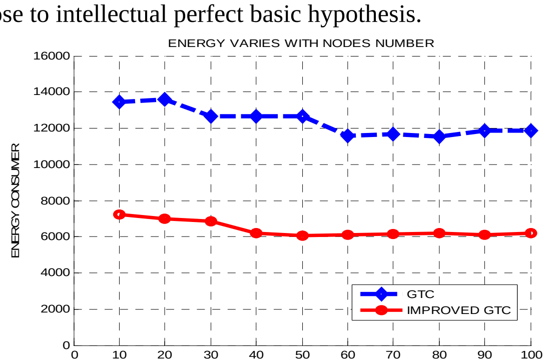

Fig.5 The comparison of GCC and Improved GCC

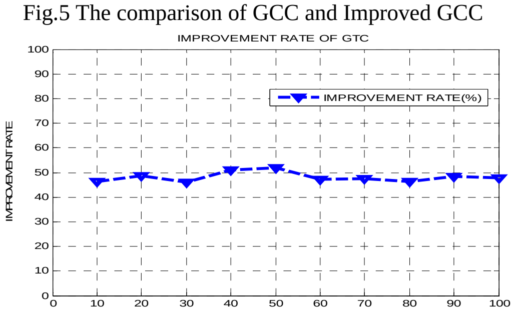

Fig.6 The improved percentage chart

V. Conclusion

From the research of this paper, we can see that to arrange resources reasonably is very important in the process when intellectual and self-organized nodes compose WSN. Using Game Theory to research WSN theory and technology is a new topic. Research and practice shows that it is a effective method, and attracts attentions of many scholars and technicians. Applying Game Theory to WSN, can solve network self-organizing problem efficiently, especially those difficult problems which cannot get analytic boundary by deduction.

After introducing basic concept of Game Theory, researching and analyzing the appliance approach in WSN, researching and analyzing WSN cognitive issue based on Game Theory and proceeding with optimization design and simulation computation, it designed a Network Full Coverage GCC algorithm, and improved it by dynamically adjust Game parameters which significantly enhanced the integrality and robustness. Simulation proves the algorithm of this paper is simple and efficient, also has strong applicability. It is the very advanced method which solved the coverage issue of WSN.

The algorithm of this paper provides a Game Theory analytical method based on Network Cognitive Basis to the research and engineering design of WSN. And it has good value of technology transferring. In the following research, a quantitative and controllable calculus of Network Coverage and Energy Control can be considered, meanwhile, adopting approaches like dynamic Game, multidimensional Game, Cognitive Learning and so on, using multidimensional network control parameters to optimize network topological structure, to proceed deep research of cognitive structure and its optimization of WSN.

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