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Power Control in Non-uniform Wireless Sensor Networks Based on the Parallel Ant Colony Algorithm

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Abstract: Energy consumption is the most important problem in wireless sensor networks. Considering the non-uniform network, a new mechanism of power control based on the PACA (parallel ant colony algorithm) is presented for the energy consumption optimization. The mechanism can search the solution space and optimize the route of data transmission to homogenize the energy consumption of the nodes. In the simulation, three different network nodes distribution are adopted and the new mechanism is compared with the fixed power routing method. The results show that the new mechanism can homogenize the nodes' energy consumption and extend the whole network's life effectively.

Keywords- Wireless Sensor Networks, Power Control, Parallel Ant Colony Algorithm

I. INTRODUCTION

The nodes of WSN (wireless sensor networks) are widely distributed in the harsh area and hard to maintain, so that WSN is an energy constrained network. In the design of a wireless sensor networks, optimization of energy consumption is a critical issue which is the key to extend the life of the network. There are already some researches which show that the nodes nearest to the sink node always have much higher energy consumption than others, leading the whole network to collapse quickly. In this case, it is necessary to develop an effective method to decline these nodes' energy consumption to let their energy be similar to others' [1]. The power control mechanism is the effective way to solve this problem. The power control mechanism is a kind of methods to reduce the energy consumption by optimizing data transmission power. The solutions of the power control always are approximate, such as LMST [2], RNG, DRNG, DLSS [3] and so on.

In this paper, our mechanism is letting the algorithm be operated all by the nodes, and the Embedded MCU on each node has limited capacity of computing. So that, we need to divide the algorithm into some smaller parts which can be parallel run by each node. In the following sections, a type of parallel ant colony algorithm (PACA) is used to implement this mechanism

In real life, a single ant's ability and intelligence are very simple, but they can complete quite complicated work such as nesting, foraging, migrating and cleaning nest by coordinating, dividing the work and cooperating. Through observing and researching the foraging of the ant colony, scientists found that ants can always seek a shortest path between the food and the nest. The ants leave the pheromone by which they communicate with each other when they are passing the path. At first, ants search the route randomly and then concentration of the pheromone increases more quickly in the shorter path than that in the longer as time passes. The following ants will be attracted by the higher concentration of the pheromone so that they are more likely to choose the shorter path and at last the ants can find a shortest route from the nest to the food.

Ant colony algorithm has natural parallelism. In the algorithm, artificial ants explore the solution space independently so that the algorithm can be separated into some parts which execute concurrently and through communicating with each other, the whole algorithm is complicated. Because of this feature the parallel ant colony algorithm is used to achieve the power control mechanism. By this method, computer is not needed any more, and the nodes can complete the task of choosing the data transmission power all by themselves.

II. NON-UNIFORM NETWORK ENERGY CONSUMPTION MODEL

In our study, a general model of WSN shown as Figure 1 is used. We use cc2430 as RF module which has eight grades of emitting power. In order to research the network conveniently, we do some assumptions:

1) The entire wireless network coverage area is round and all network nodes are distributed in a circular area which sink node is located above the center of the circular area.
2) All the nodes in the network non-uniformly distribute. And all the nodes belong to the same type, which have the same function, energy, etc. Each node is all utility nodes, and has the ability to send and receive and transmit data.
3) On the network nodes, the RF modules have fixed launch distance, which won't change because of energy reducing or interference.
4) Don't consider mutual interference problems in the process of the signal transmission, namely the signal from the send node must be received by the receive node, and that there are no problems for

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channel.

5) Don't consider data fusion.

6) Sink node receives and processes all the data sent to it.

The sink node locates in the center of the area and all nodes do not distribute uniformly.

The whole monitored area is divided into some zones [4]. Each zone has the same width r which is the distance that the nodes transmit the data by using the lowest emitting power. The sink node lie in the zone 0, the nodes with grade 1 lies in the zone 1, and so on. If all the nodes use the lowest power to transmit the data, the data from the nodes with grade k will be retransmitted k-1 times until it arrivals the sink node.

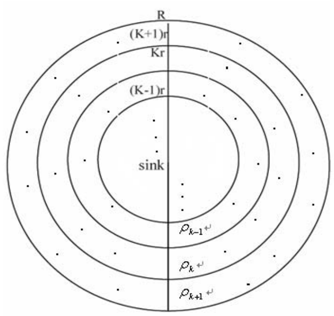

Fig. 1: Wireless sensor networks model

In this model, we assume that the distance between the sink node and the farthest nodes is R.

In the area, the density of the nodes in different zones is not the same, which means that the nodes are not uniformly distributed. We assume that the density of the nodes with grade k is ρ_k. So that, the density vector of the whole network is:

$$\rho = \{\rho_1, \rho_2, ..., \rho_p\}$$

Each node can produce one data packet per unit time and the nodes with grade k can only transmit data to the nodes with a higher grade such as grade k-1. We ignore the data fusion here.

We suppose the RF module we use have eight grades of emitting power, and the distances of every power are:

$$Radius = \{r, 2r, 3r, 4r, 5r, 6r, 7r, 8r\}$$

While the eight values of the sending power are:

$$Power = \{p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8\} = \{1, 4, 9, 16, 25, 36, 49, 64\}$$

And the receiving power is pr=3. Then each node has four choices to send data packet to. For example, the nodes with grade k can transmit data to the nodes with grade k-1, k-2… and k-8.

There are $\pi((kr)^2 - ((k-1)r)^2)\rho_k$ nodes with grade k and $\pi(((k+n)r)^2 - ((k+n-1)r)^2)\rho_{k+n}$ nodes with grade k + n. So the ratio of their number is:

$$\frac{2k+2n-1}{2k-1} \times \frac{\rho_{k+n}}{\rho_k} \quad (1)$$

We assume that probabilities of the nodes with grade k choose the eight grades of emitting power are $P = \{\lambda_1^k, \lambda_2^k, \lambda_3^k, \lambda_4^k, \lambda_5^k, \lambda_6^k, \lambda_7^k, \lambda_8^k\}$. We can get the number of data packets received by the node with grade k:

$$Rd(k) = \sum_{n=1}^{8} \lambda_n^{k+n} Td(k+n) \frac{2k+2n-1}{2k-1} \times \frac{\rho_{k+n}}{\rho_k} \quad (2)$$

Besides retransmitting the data packets, every node also produces its own data packet, one per unit time. As a result, packet number sending by each node with grade k is:

$$Td(k) = Rd(k) + 1 \quad (3)$$

Considering the energy consumption of the control frames, in the communication based on the RTS-CTS handshaking protocol, we know [5]:

$$Rd(k) = Rrts(k) = Tack(k) = Tcts(k) \quad (4)$$

$$Td(k) = Trts(k) = Rack(k) = Rcts(k) \quad (5)$$

Without considering other energy consumption, the energy consumption used to send a control frame is as $42/282 \approx 0.15$ times as that used to send a data frame. Based on the above equations we can obtain the energy consumption of the nodes with grade k after each node in the network has sent a data packet [6]:

$$\begin{aligned} Q(k) = {} & (\sum_{n=1}^{8} \lambda_n^k p_n)(Td(k) + 0.15Trts(k)) \\ & + (\sum_{n=1}^{8} \lambda_n^{k+n} p_n)(Tack(k) + Tcts(k)) \\ & + p_r(Rd(k) + 0.15(Rack(k) + \\ & Rrts(k) + Rcts(k))) \end{aligned} \quad (6)$$

Through simplifying the equation, we get:

$$\begin{aligned} Q(k) = {} & 1.15(\sum_{n=1}^{8} \lambda_n^k p_n) Td(k) \\ & + 0.3(\sum_{n=1}^{8} \lambda_n^{k+n} p_n) Rd(k) \\ & + p_r(1.15Rd(k) + 0.3Td(k)) \end{aligned} \quad (7)$$

Equation above is the energy consumption of the nodes with grade k.

Our goal is to optimize the probabilities, λ_n^k to reduce maximum and sum of energy consumption.

III. Optimization on PACA

In the section two, we have discussed the energy consumption model of the nodes in non-uniform WSN. Obviously, the energy consumption is related to which grade of emitting power the nodes choose to transmit data [7]. So we consider adjusting the emitting power to optimize the energy consumption. It seems that the lowest grade of power is the best choice but the experiment result shows that all the nodes using the lowest power as the data is transmitted grade by grade will let the energy consumption of the nodes with grade 0 is much higher than that of other nodes, and the whole energy consumption is also not good enough. As a result, we use another emitting power tactic and trail its effectiveness through the simulations.

After observing the issue, we find that the process of transmitting the data packet from some nodes to the sink node can be looked upon as the ant finding the way to the food. So we can imagine a data packet sent by the nodes as an ant and the ant find the best route from the start node to the sink node. Then the problem is transformed to the food recruitment of ants which can be solved by ant colony algorithm.

The ant colony has natural parallelism and the ants in different grades search the path to the sink node independently. So we consider that the algorithm can be transformed to a parallel version which is divided to some parts executed by the nodes with different grades concurrently. Our goal is to realize a self-organization network. It means that the WSN nodes can compute by themselves which grade of emitting power they should choose when they want to send data packets so the network do not need computer to complete these tasks.

We assume that there are n grades of nodes in the network and p grades of emitting power of the RF module. So the nodes with grade k have p choices which are grade k-1, grade k-2, grade k-3… and grade k-p to transmit the data packet. It forms a $p \times n$ matrix. Each element stands for the probability of the data transmission from one grade of nodes to another. And it also forms another $p \times n$ matrix storing the pheromone between the nodes with grade k and their adjacent p grades.

At the beginning, we lay ants on each grade, one ant one grade. The ants with different grades move to the sink node based on the probability matrix shown as the following Table 1. S_n indicates the nodes with grade n. D_p indicates the grade p of emitting power which the nodes choose when they are sending the data. P_{ij} indicates the probability of the nodes with grade i choosing the grade j of emitting power.

Table 1: Probability Matrix

	S_1	S_2	S_3	……	S_n
D_1	P_{11}	P_{21}	P_{31}	……	P_{n1}
D_2	—	P_{22}	P_{32}	……	P_{n2}
……	……	……	……	……	……
D_p	—	—	—	……	P_{np}

The probability P_{ij} can be described by the following equation [8]:

$$P_{ij}(t) = \begin{cases} \dfrac{\tau_{ij}^{\alpha}(t)\eta_{ij}^{\beta}(t)}{\sum\limits_{s \in allowled(i)} \tau_{is}^{\alpha}(t)\eta_{is}^{\beta}(t)} & j, s \in allowed \\ 0 & otherwise \end{cases} \quad (8)$$

$allowed = \{1, 2, ..., p\}$: The p grades of emitting power.

$\tau_{ij}(t)$: The value of the pheromone on the way between t and j at time t.

$\eta_{ij}(t)$: Heuristic factor related to the energy consumption when the nodes with grade i choose the grade j of emitting power. Here,

$$\eta_{ij}(t) = \frac{1}{Q_{ij}} \quad (9)$$

Q_{ij} : The energy consumption when the nodes with grade i choose grade j of emitting power to send the data.

α : The weighing of the pheromone.

β : The weighing of the heuristic factor.

Similar to the probability matrix, the pheromone matrix is also a $p \times n$ matrix whose elements are the pheromone: $\tau_{ij}(t)$. And the rule of pheromone update is

$$\tau_{ij}(t) = \begin{cases} (1-\rho) \cdot \tau_{ij}(t-1) + \sum\limits_{k=1}^{m} \Delta\tau_{ij}^{k}(t) & \\ \tau_{\min} & if\ \tau_{ij}(t) < \tau_{\min} \\ \tau_{\max} & if\ \tau_{ij}(t) > \tau_{\max} \end{cases} \quad (10)$$

Here, we use the Max-Min pheromone update regulation (MMAS). We set maximum and minimum of pheromone for avoiding the pheromone be too large or too small. In the above equation,

$\tau_{\min}$: The minimum of pheromone.

$\tau_{\max}$: The maximum of pheromone.

$\rho \in (0,1)$: Evaporation of pheromone.

$\Delta\tau_{ij}^{k}$: The value of pheromone update left by the ants which have passed the path. And,

$$\Delta\tau_{ij}^{k}(t) = 1 / (\max(Q(m)) - \frac{sum(Q(m))}{n}), m \in M \quad (11)$$

M is the set of all grades of nodes. $\max(Q(m))$ is the maximum of energy consumption nodes when all the nodes have sent a data packet to the sink node. $sum(Q(m))$ is the sum of all the nodes energy consumption. n is the number of the grades of network.

To realize parallel ant colony algorithm, we use the WSN nodes execute their own parts of the algorithm, and the nodes communicate with each other to update the energy consumption, pheromone matrix and probability matrix, and in the end the nodes complete all the task of the algorithm by themselves.

The computational capabilities and the memory space of the nodes are limited. So we must reduce the space complexity of the algorithm in order to make sure that the algorithm can be executed in the nodes.

Through observing the algorithm, the pheromone matrix, heuristic matrix, probability matrix and path matrix are the biggest space requirement. So we divide the matrix into some parts as below. One grade of the nodes just store one column of the matrix not all the matrix. The values of the column which the node keeps are the neighbors that this node can reach when they send data. For example, in the probability matrix, the nodes with grade i just need to keep $P_{i1}, P_{i2}, ..., P_{ip}$, similar in the pheromone matrix, just $\tau_{i1}, \tau_{i2}, ..., \tau_{ip}$ should be stored and the heuristic matrix also just need $\eta_{i1}, \eta_{i2}, ..., \eta_{ip}$. The node with grade i just store the energy consumption itself and the next hop layer not the whole energy consumption vector or the whole path matrix. And space requirements of other parameters are much smaller than the matrix of pheromone and probability, so there is no need to do any special change.

At first we select nodes in the network, which establish the straight line, involved in the algorithm execution. A total of n lines are required. K-line to send data starting point is the k layer nodes, and the end is the sink node.

Different grades of nodes execute parts of the algorithm independently, and communicate with each other to update the pheromone and probability when a generation finishes. In this way, when reaching the iteration which is set at the very beginning or the solution contents some special conditions, the process stops and we get final solution: the optimal probability matrix. In the future application, the nodes choose the grade of emitting power to send data by their own columns in the probability matrix. The algorithm process is shown as the Figure 2.

We set an inner iteration number M, and update the pheromone matrix by using the best solution in the M generations. The purpose of this method is to increase the capacity of the exploration to the solution space, and to avoid being premature constringency which can lead the algorithm to fall into local optimum.

The algorithm is executed before the nodes start to work formally, and when the algorithm finishes, the nodes store the probabilities of choosing the grade of emitting power. The nodes transmit data by the probabilities and the result does not need to be recalculated until the network's construction change because of some nodes dying or other reasons.

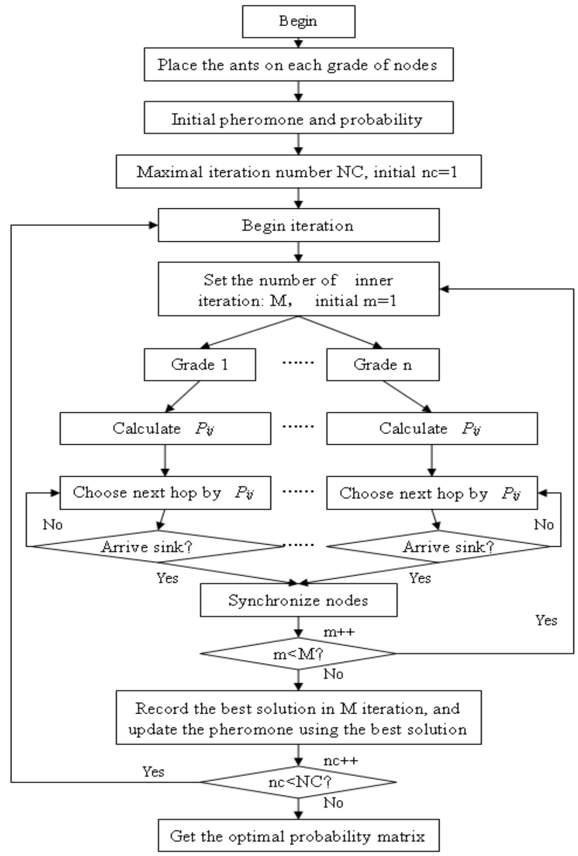

Fig. 2: The process of PACA

IV. Simulation and Results

Figure 3, Figure 5 and Figure 7 show the results of using the fixed grade of emitting power (FP). The results are the values of the nodes' energy consumption when all the grades of nodes have sent a data packet to the sink node. the nodes with grade 1 have the highest energy consumption which is much higher than other nodes'. Comparing with the method of transmitting data grade by grade, Figure 4, Figure 6 and Figure 8 show the results of using the new mechanism based on the parallel ant colony algorithm. Obviously, this method can reduce the maximal energy consumption effectively, and balance the energy consumption of the nodes near to the sink node.

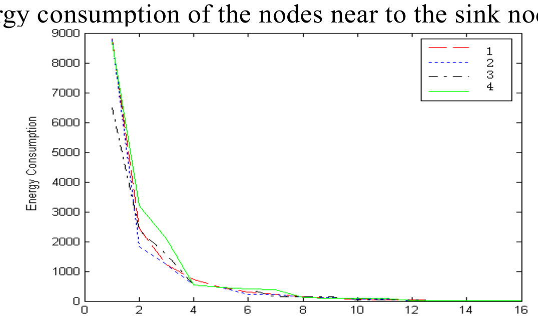

Fig. 3: Energy consumption of FP routing (T=1.2)

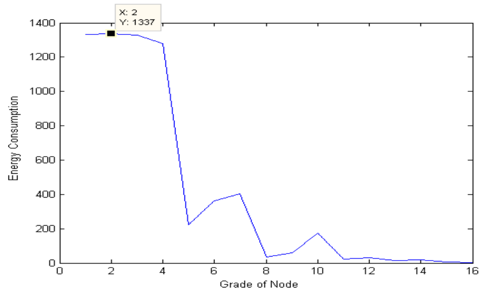

Fig. 4: Energy consumption of PACA (T=1.2)

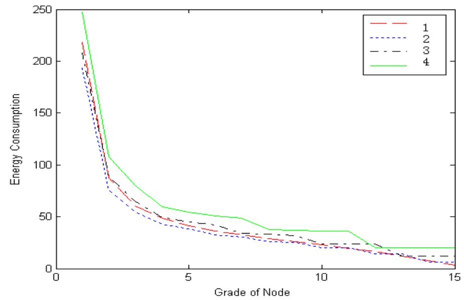

Fig. 5: Energy consumption of FP routing (T=0.8)

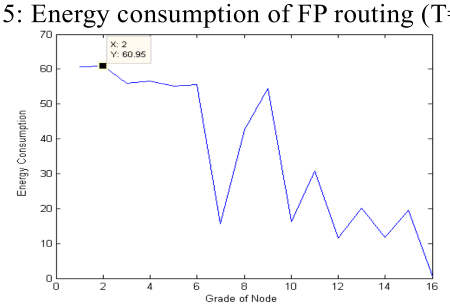

Fig. 6: Energy consumption of PACA (T=0.8)

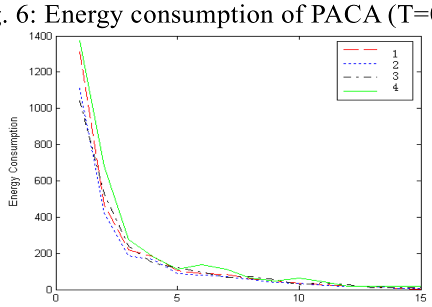

Fig. 7: Energy consumption of FP

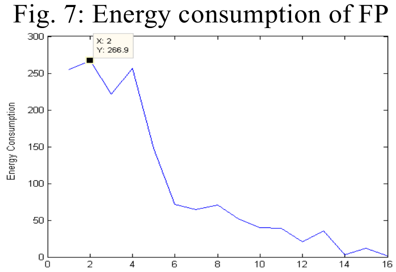

Fig. 8: Energy consumption of PACA (random density)

The results of the simulation are shown as the following Table 2. We choose the best result of fixed power for contrast: (FP: Fixed Power; PACA: Parallel Ant Colony Algorithm; Random: Density Random)

Table 2: Simulation Results

	FP T=1.2	PACA T=1.2	FP T=0.8	PACA T=0.8	FP Random	PACA Random
Sum(Q)	12459	6625	600	568	2495	1555
Max(Q)	6483	1337	193	61	1041	267

In the condition, T=1.2, the sum of energy consumption based on PACA is 0.532 of that based on Fixed Power (FP) and the maximum of energy consumption based on PACA is 0.206 of that based on FP. In the condition, T=0.8, the sum of energy consumption based on PACA is 0.947 of that based on FP and the maximum of energy consumption based on PACA is 0.315 of that based on FP. In the condition, density random, the sum of energy consumption based on PACA is 0.632 of that based on FP and the maximum of energy consumption based on PACA is 0.256 of that based on FP.

V. CONCLUSIONS

In this paper, a new mechanism based on parallel ant colony algorithm is presented to reduce the maximum and the sum of the energy consumption and homogenize the energy cost of the nodes. In the network model, the nodes distribute unevenly. This parallel algorithm also lets the nodes complete the whole routing work by Embedded MCU and the computer is not needed any more. In the end, the algorithm gets the probability matrix by which the nodes choose the emitting power. The simulation results show that the new mechanism has decent capacity in these objectives.

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