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A Nonlinear Multiple-target Coverage Protocol Based on Data Integration of Wireless Sensor Networks

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Abstract

In the process of coverage for multiple targets, due to the existence of a large number of redundant data make the effective monitoring area coverage decreased and force the network to consume more energy. Therefore, this paper proposes a multi-target k-coverage preservation protocol. First of all, establish the affiliation between the sensor nodes and target nodes through the network model, present a method to compute the coverage expected value of the monitoring area; secondly, in the network energy conversion, using scheduling mechanism in sensor nodes to attain the network energy balance, and achieve different network coverage quality through different nodes energy conversion. Finally, simulation results show that NMCP can effectively reduce the number of active nodes meeting certain coverage requirements and then improve the network lifetime.

Keywords: *wireless sensor network (WSN); network lifetime; coverage rate; multi-targets; preservation protocol*

1. Introduction

As technologies advance, wireless sensor network (WSN) technology gains rapid development. WSN is the network system constituted by a large number of randomly scattered or self-organized low-cost sensor nodes. These nodes display their features in the calculation, sensory, communication, storage and control ability [1-2]; and in terms of their actions, they can integrate the physical world and the information world, achieving the network service system for data collection, calculation, communication and control [3]. In the engineering field, WSN has been widely utilized in many sectors such as military and national defense, traffic and transportation, medicine and health, environmental monitoring and emergency rescue. Take the battlefield as the example, WSN presents the coverage figure with multiple K values, as shown in Figure 1.

Coverage quality and energy management, as two hot issues in the WSN research, are also two critical indices for the performance of the SWN structure [4]. The nature of coverage dose not refers to full coverage over the monitoring area, but over the focused targeting nodes. The coverage quality imposes direct influence not only on both the attention on the targeting nodes but also on the life circle period of the network and the network service quality [4-5]. If multiple-target nodes are to be covered, K-coverage model can be adopted. Generally speaking, sensory nodes are randomly scattered in the monitoring area, which may result in excessive nodes in certain location and thus put this

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area in high-density deployment. In this way, there will be a large number of redundant nodes that can disturb the communication channel to weaken communication ability between nodes, increase the network energy consumption and limit the further expansion of the network.

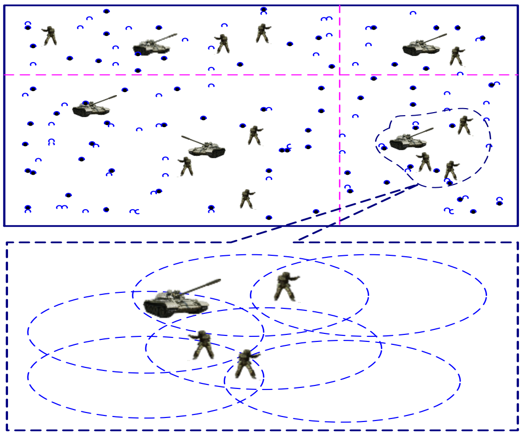

Figure 1. The Figure of *K*-Coverage

2. Relevant Researches

For recent years, many scholars at home and broad have made productive researches on the wireless sensor network coverage and made certain progress in this field. In Reference [5], the connectivity-coverage scheduling control algorithm (SCA) was put forward. With this algorithm, one can calculate the probability of sensor nodes covering any targeting node in the monitoring area through solving the function of the relation between the network connectivity and coverage quality, and dynamically adjust the distribution of active nodes to balance the network energy as a whole. Reference [6] proposed the distributed node coverage algorithm. This algorithm divides the monitoring area into different sub-areas to obtain Voronoi figure and demonstrates the affiliation between the maximum and minimum edges and the maximum and minimum angles of polygons in the sub-areas via geometric calculation. Then through iterative optimization of every result, all sub-areas are covered as expected. Reference [7] suggested calculating the network coverage rate via the artificial bee colony algorithm and particle swarm optimization, with its essence of iteratively refining local solution set based on the two artificial algorithms and limiting the "overflow" of the locally optimal solution. And concerning the overall optimization, the fitness function is used to optimize the locally optimal solution set for the overall optimal solution so as to cover the whole network system. Reference [8] put up with a strategy to restore and optimize uncovered areas which reasonably increase and optimize sensor nodes in uncovered areas with the premise of certain coverage rate. This strategy, via geometric graphics, calculates the uncovered area and sensor nodes and find out the best uncovered location for restoration so as to lessen sensor nodes and ensure the network connectivity. Reference [9] proposed the K-grade barrier coverage algorithm based on the maximum network life cycle which presented the method of calculating the ceiling and floor of coverage rate at the theoretical level. In terms of the energy conversion of sensor nodes, the greedy algorithm is adopted to optimize the communications channel among sensor nodes to finally achieve network energy balance. In Reference [10], the event-probability-driven mechanism (EPDM) was presented. This mechanism builds up the network probability model, calculates the coverage rate of any sensor node within the monitoring area and gives procedures to prove *K*-coverage of targeted nodes among active nodes. In choosing the channel, the ant colony algorithm is used to find the optimal one to save the network energy. Reference [11] put forward the energy-efficient target coverage algorithm (ETCA) based on linear programming. With this algorithm, the target nodes can be classified via linear programming and various target sets can be effectively covered by clustering. Then through calculation, the rest energy of sensor nodes will be balanced to effectively cover the monitoring area. Reference [12] proposed the coverage conserving protocol and gave the model for calculating the redundancy rate of the normal distribution of the radius of sensor nodes without location, achieving the sensor nodes distribution scheduling mechanism, efficiently covering the monitoring area and extending the network life cycle. Such a algorithm can realize better coverage and reduce the energy consumption of sensor nodes through the energy scheduling mechanism, but is of high complexity and calculation burden. Reference [13] presented the distribution-oriented self-moving scheduling and programming algorithm that covers the target nodes via a set of self-moving sensor composed by sensor nodes. When the moving target node enters the set, the nodes in the set that has completed coverage for the first round will transfer the configuration protocol to the next sensor node to finish the whole covering process of the set. Despite its ability to cover the target nodes, this algorithm is too ideal to achieve the comprehensive coverage in real situation. Reference [14] proposed a coverage algorithm based on sensory perception model which calculates the rate of sensor nodes coverage in the monitoring area via Exponential distribution characteristics, and then presents the calculation procedures for coverage quality via the rate. This algorithm, though it can effectively cover certain monitoring area, is very complex to calculate. Reference [15] put up with a node distribution algorithm for the largest coverage based on genetic algorithm. This method introduces the genetic algorithm into the solution set, builds a solid evaluation function via Monte Carlo method and then increases the number of the next generation in the random sample and optimizes them so as to get coverage balance. This algorithm fastens the coverage to some extent as required, but ignores the energy consumption of nodes. The coverage algorithms proposed in Reference [16-18] are all based on the location of sensor nodes to get the coverage rate, which can effectively cover the monitoring area theoretically. But additional positioning equipment like GPRS is needed to obtain the node location, increasing the cost of network system operation and strengthening disturbance among signals. In this case, the coverage relation of sensor nodes cannot be precisely calculated. Reference [19], taking wireless sensor network coverage as the premise and the clustering structure as the object, proposed a self-adaptive WSN stratified data collecting frame, in which data analysis and collection are conducted via clustering nodes as well as the prediction model. This frame integrates the data collected, but ignores node energy consumption. Reference [20-23], based on researches on effective coverage, put up with node energy conversion model, decreasing the node energy consumption and the cost of node energy, but weakening the coverage effect. In Reference [24], Wu proposed a protocol for localizing the distribution of connected dominating set and discussed the method of energy-conservation dominating set coverage. And to balance the network energy consumption, the rest energy is used to give a way to choose the nodes to be covered. All these continuously cover the target nodes via static nodes which is no need in the application, while the use of certain number of movable nodes generate higher efficiency than mere static nodes.

3. Network Model and Coverage Quality

To better study WSN coverage and NMCP algorithm, this paper made following assumptions:

(1) All sensor nodes have perception ability with disc-shaped perception and communication range.
(2) The perception radius of sensor nodes is much less than the side length of the monitoring area.

(3) At the initial moment, all sensor nodes are of equal energy and in line with the clock.
(4) All information about the location of sensor nodes is obtained by GPRS.
(5) The perception radius of sensor nodes is in normal distribution.

3.1 Basic Definition

Definition 1: (Target Coverage) In the two-dimensional plane, any target node is covered by at least one sensor node, which refers to target coverage.

Definition 2: (K-coverage) In the monitoring area, any target node is covered by sensor nodes with their number as *K*, which refers to *K*-coverage.

Definition 3: (Network Life Cycle) The time range from the network operation to the moment any target node in the monitoring area cannot be covered by sensor nodes is called network life cycle.

Definition 4: (Coverage Quality) In the two-dimensional plane, the ratio of total perception area of sensor nodes and total monitoring area is called coverage ratio.

3.2 Coverage Quality

Theorem 1: In K-coverage with *K* as 2, the coverage rate of any target node is set as *p*. m and n were the moving times of sensor nodes with the occurrence probability as p^2q^{n-2} and contingent probability as pq^{n-m-1}. Here, q=1-p.

Proof: Set *X* as the moving times of nodes in the first round and *Y* as that in the second round. As can been seen, in the first round, the target node is covered by sensor nodes at m times. And in the second round, the target node is covered by sensor nodes for twice at n times and uncovered at *n*-2 times. Thus, the occurrence probability of sensor nodes is:

$$P\left(X=m,Y=n\right)=p^2q^{n-2} \tag{1}$$

And the combined probability of the first and second round is:

$$\begin{aligned}P\left(X=m\right)&=\sum_{n=m+1}^{\infty}P\left(X=m,Y=n\right)\\&=\sum_{n=m+1}^{\infty}p^2q^{n-2}=pq^{m-1}\end{aligned} \tag{2}$$

$$\begin{aligned}P\left(X=n\right)&=\sum_{m=1}^{n-1}P\left(X=m,Y=n\right)=\sum_{m=1}^{n-1}p^2q^{n-2}\\&=\left(n-1\right)p^2q^{n-2}\end{aligned} \tag{3}$$

The multiplication formula of probability leads to:

$$\begin{aligned}P\left(Y=n\middle|X=m\right)&=\frac{P\left(X=m,Y=n\right)}{P\left(X=m\right)}\\&=\frac{p^2q^{n-2}}{pq^{m-1}}=pq^{n-m-1}\end{aligned} \tag{4}$$

Proving over.

Theorem 2: Set the coverage rate of any sensor node as *p*, and then the coverage rate of any node in the two-dimensional plane is $P(nA)=1-(1-p)^n$.

Proof: Mathematical Induction is adopted for proof. In the two-dimensional plane, nay sensor node is dependent on each other. According to the probability theory, if *K*=2, then

$$P(A+A)=p(A)+p(A)-p(A)p(A)=1-(1-p)^2 \tag{5}$$

If *K*=3, then the combined probability is:

$$P(A+A+A)=p(A+A)+p(A)-p(A+A)p(A) \tag{6}$$

If Formula (6) is applied into Formula (5), then:

$$P(A+A+A)=1-(1-p)^3 \tag{7}$$

If $K=i$, Formula (7) leads to:

$$P(nA)=1-(1-p)^n \tag{8}$$

Proving over.

Assumption 1: In the two-dimensional plane, the coverage rate of sensor nodes is p and N the largest times of the continuous coverage of the nodes. Until the moving target nodes are covered, the expected sensor node coverage rate is $E(X)=[1-(1-p)^N]p^{-1}$.

Proof: In the two-dimensional plane, if the moving times of the target nodes is X, then $X\in[1,2,3\ldots N]$ as N is the largest times of the continuous coverage of sensor nodes. If $X=m$ and $1\le m\le N-1$, namely the target node is not covered by sensor nodes with the times from 1 to N-1, then the distributive density function of X in line with the probability theory is:

$$P(X=k)=\begin{cases} p(1-p)^{k-1} & k=1,2,3\cdots N\text{-}1 \\ (1-p)^{N-1} & k=N \end{cases} \tag{9}$$

Namely:

$$E(X)=\sum_{k=1}^{N-1}kp(1-p)^{k-1}+N(1-p)^{N-1} \tag{10}$$

If $q=1-p$, $S=\sum_{k=1}^{N-1}k(1-p)^{k-1}$,then $S=\sum_{k=1}^{N-1}kq^{k-1}$. If q is multiplied by both sides then $qS=\sum_{k=1}^{N-1}kq^{k}$,or specifically:

$$(1-p)S=\sum_{k=1}^{N-2}q^k-(N-1)q^{N-1}=\frac{1-q^{N-1}}{1-q}-(N-1)q^{N-1}$$

$S=\dfrac{1-q^{N-1}}{(1-q)^2}-\dfrac{(N-1)q^{N-1}}{1-q}=\dfrac{1-(1-p)^{N-1}}{p^2}-\dfrac{(N-1)(1-p)^{N-1}}{p}$ if s is applied to Formula (10), then:

$$\begin{aligned} E(X)&=p\left(\frac{1-(1-p)^{N-1}}{p^2}-\frac{(N-1)(1-p)^{N-1}}{p}\right)+N(1-p)^{N-1} \\ &=\frac{1-(1-p)^{N-1}}{p}-(N-1)(1-p)^{N-1}+N(1-p)^{N-1} \\ &=\frac{1-(1-p)^{N-1}+p(1-p)^{N-1}}{p}=\left[1-(1-p)^N\right]p^{-1} \end{aligned} \tag{11}$$

4. NMCP Protocol

4.1 Energy Conversion

The energy consumption of sensor nodes usually lies in such two parts as perception part and communication part. If the data collected is l bit, the energy consumption of perception part and communication part are respectively E_T and E_R:

$$E_T(l,d)=\begin{cases} lE_{T-elec}+l\varepsilon_{fs}d^2\ , & d<d_0 \\ lE_{T-elec}+l\varepsilon_{amp}d^4\ , & d\ge d_0 \end{cases} \tag{12}$$

The energy consumption model of receiving module is:

$$E_R(l)=E_{R-elec}(l)=lE_{elec} \tag{13}$$

l bit is the fixed length of data transmission, d the communication distance (Euler) between sensor nodes, d_0 the threshold value of communication distance. If $d<d_0$, then the energy declining index is 2, otherwise the index is 4.

Definition 5: (Optimal Subset) Set the WSN sensor node set as G. If in the unit time, a senor node subset $G_1 \subset G$, which makes all sensor nodes cover the target set T, then G_1 is the subset of G.

Definition 6: (Energy Property) $W=\{w_1,w_2,w_3 \ldots w_n\}$ refers to the set of initial energy of sensor nodes, and W conforms to the $W \sim N(\mu,\sigma^2)$ normal distribution. w_i represents the initial energy of the sensor node s.

Definition 7: (Maximum Distortion Amount) with the premise of certain coverage rate, the maximum distortion amount is

$$E\left[\left(s_1(x,y)-s(x,y)^2\right)\right] \le D \quad \forall s_i(x,y) \in A \tag{14}$$

$s_1(x,y)$ is the estimated value of the Euler distance between sensor nodes and target nodes and $s(x,y)$ the average measured value of the Euler distance between the two.

Theorem 3: The distance between sensor nodes is less than or the same as the difference of the variance and half of the distortion value.

Proof: Set the measured value of the sensor node $t(x,y)$ as $s(x,y)$, and the data used contains the measured one. And if the multiple-target nodes are to be measured, the average value is all in line with normal distribution. The energy set of sensor nodes with fixed energy is $W=\{w_1,w_2,w_3 \ldots w_n\}$. The Euler distance between communication nodes is:

$$\begin{aligned} R((x_1,y_1),(x_2,y_2)) &= \sqrt{(x_1-x_2)^2+(y_1-y_2)^2} \\ &= E\left[\left(S(x_1,y_1)-u\right)\left(S(x_2,y_2)-u\right)\right] = R(d) \end{aligned} \tag{15}$$

Set H as the set of sensor nodes with data collected, then H_1 is the complementary set. The measured value of the sensor node closet to the target node in H is used to estimate a signal data in H_1. So the estimated signal value $s_1(x_0,y_0)$ at the target node (x,y) is

$$s_1(x_0,y_0)=s(x_1,y_2) \tag{16}$$

And Formula (14) and Formula (15) lead to :

$$\begin{aligned} E\left[\left(s(x_0,y_0)-\mu\right)\left(s(u,v)-\mu\right)\right] &= E\left[\left(s_1(x_0,y_0)-s(u,v)\right)^2\right] \\ &= 2\sigma^2-2R\left(d\left((x_0,y_0),(u,v)\right)\right) \end{aligned} \tag{17}$$

Apply Formula (14) to Formula (17), then

$$R\left(d\left((x_0,y_0),(u,v)\right)\right) \le \sigma^2 - D/2 \tag{18}$$

Proving over.

4.2 NMCP Algorithm Philosophy

According to the basic idea of Reference [11], based on the clustering technology theory, the monitoring area is divided into several sub-areas, and every cluster head node manages and controls the other nodes in the cluster. At the initial stage of network operation, nodes in the cluster first send the message “*K*-coverage” to the head node. Then the head node builds a chain table and stores the information received in this table, including ID of sensor nodes, the perception extension and energy declining. After one cycle or several cycles, the head node receives all the information sent by nodes in the cluster, then classifies and ranks the information in the table according to the rest energy of nodes and grants certain value to the nodes before the table. Next is to search for the sensor nodes qualified for the coverage of the target node and mark them. At last, the head node sends “*K*-Notice” to other nodes in the cluster, and qualified sensor nodes are to cover the corresponding target nodes.

4.3 Procedures of NMCP Algorithm

Step 1: Calculate the perception intensity of nodes in the cluster.

Step 2: Nodes in the cluster sends "*K*-coverage" to the head node. After one or several unit hours, the head node receives information sent from other nodes in the cluster.

Step 3: The head node receives all the information sent by nodes in the cluster, then classifies and ranks the information in the table according to the rest energy of nodes and grants certain value to the nodes before the table.

Step 4: Search for and mark the qualified sensor nodes.

Step 5: If the target node is under the *K*-coverage, the head node will search in the chain table via traversal to close the sensor node with low perception intensity.

Step 6: After traversal in the table, the head node schedules the optimal subset to cover the target nodes. Otherwise, return to Step 2.

4.4 Analysis of the Complexity of NMCP Algorithm

In the analysis of NMCP algorithm, n represents the number of sensor node, m equals to the number of edges connected between any two sensor nodes. P_{min} and P_{max} are the minimum and maximum coverage value of the monitoring area. Δp means the increment of coverage after each covered process. Set $P_{min}=c$, $P_{max}=bn$, c and b are constant coefficient. Assume: At the initial moment, the coverage percentage of sensor node is $p(0)=b/n$, at time t, the transition probability of a sensor node is greater than c/2bn which also means the minimum probability of sensor node's coverage $P_{min}=c/2bn$. Set $R=(1-e)p(t-1)$ *at time* $t+1$, the coverage of a sensor node is:

$$\begin{aligned} p(t+1) &= \frac{p_{t+1}(t+1)}{p_{t+1}(t+1)+p_t(t+1)} \\ &\le \frac{p_{t+1}(t+1)}{c+p_t(t+1)} \le \frac{b}{(1-\Delta p)(c+ce+R)} \end{aligned} \tag{19}$$

When $L=\frac{b}{(1-e)(c+ce+R)}$, the time complexity of NMCP algorithm is $E(T)$ which is the following

$$\begin{aligned} E(T) &= \sum_{m=1}^{n-1}\left(\frac{2bn}{c(n-m)}\cdot\left[1-\frac{L}{n}\right]^{1-n}\right) \\ &= \frac{2bn}{c}\left[1-\frac{L}{n}\right]^{1-n}\sum_{m=1}^{n-1}\frac{1}{m} \le \frac{2bn}{c}e^{-L}H_{n-1} \end{aligned} \tag{20}$$

Since $\sum_{m=1}^{n-1}\frac{1}{m}$ is the sum of harmonic series of first n-1 terms, let $H_{n-1}=\sum_{m=1}^{n-1}\frac{1}{m}$, then $\sum_{x=1}^{n-1}\frac{1}{x}-1<\int_1^{n-1}\frac{1}{x}dx<\sum_{x=1}^{n-1}\frac{1}{x}$ that is:

$$H_{n-1}=\sum_{m=1}^{n-1}\frac{1}{x}=\int_1^{n-1}\frac{1}{x}dx=O(\ln n) \tag{21}$$

5. Evaluations on the Mechanism

To further testify the validity and feasibility of NMCP algorithm, this paper, with MATLAB7 as the simulation platform, conducts simulation experiment on NMCP and Reference [10] and [11] and gives comparison of performance under different evaluation system. Parameters are shown in Table 1.

Table 1 Table of Performance Parameters

parameter	value	parameter	value
Monitoring area Ⅲ	400*400	R_c	20m
R_s	10m	$E_{\text{R-elec}}$	50J/b
Initial energy	10J	$E_{\text{T-elec}}$	50J/b
time	600s	ε_{fs}	10(J/b)/m^2
e_{min}	0.005J	ε_{amp}	100(J/b)/m^2

This paper, in the same network scale, conducts simulation experiments on the network operating time and coverage rate based on NMCP, ETCA[6], ECAPM[8] and EPDM[5] with different network life cycle, scale of target nodes and number of sensor nodes, as shown in Figure 2 to Figure 5.

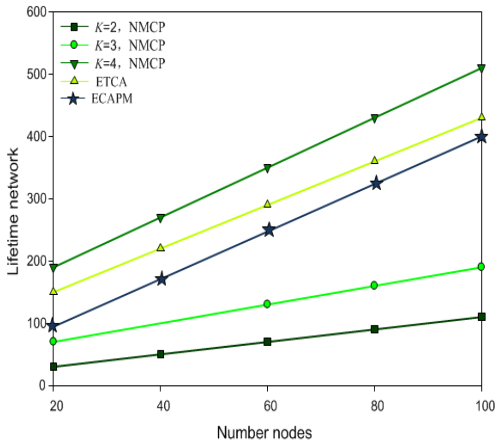

Figure 2. Comparison of Network Life Cycle

Figure 2 presents the simulation result of comparison of network life cycle based on NMCP, ETCA and ECAPM. It can be seen from Figure 2 that at the initial stage of network operation, the operating time of the three algorithms is nearly the same. However, as the time goes, ETCA and ECAPM show slower ascending speed. Because the two algorithms monitor the whole network intensively and transform the scheduling mechanism between sensor nodes via linear programming, which demands high cost of node energy. However, NMCP algorithm in this paper realizes the coverage of the monitoring area mainly through searching for the optimal node set in the chain table. With the same number of sensor nodes, NMCP demands more network operating time. Compared to ETCA with 200 times of iteration, the network life cycle based on the two algorithms extends 16.33% and 19.75% respectively.

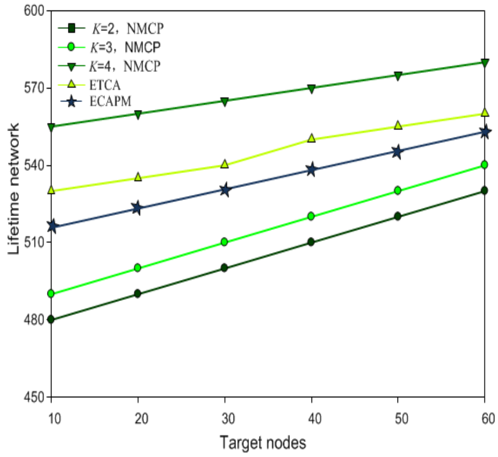

Figure 3. Network Life Cycle with Different Number of Target Nodes

Figure 3 reflects the curve of network life cycle with different number of target nodes. At the initial stage of the network operation, the number of sensor nodes is 348 with the number of 10 at the initial moment. As network operating time and the number of target nodes increase, all network life cycle based on the three algorithms is balanced. Compared to NMCP with *K*=4, ETCA and ECAPM show minor fluctuations. With the same number of target nodes, the network operating time of NMCP is more than that of ETCA with the rate of 7.12% and 9.06%.

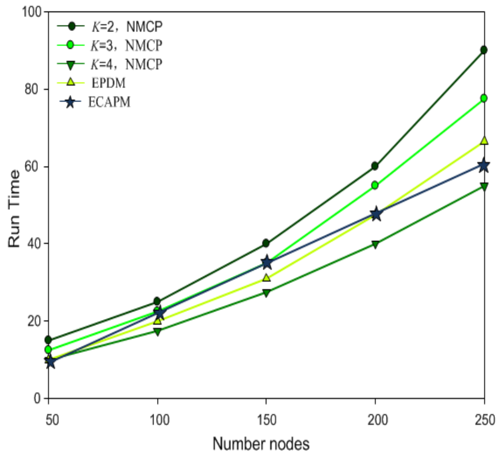

Figure 4. Comparison of Operating Time Based on Three Algorithms

Figure 4 demonstrates comparison of the operating time based on three algorithms. It can be perceived that the running time of NMCP is less than that of EPDM and ECAPM, mainly because the clustering structure of NMCP enables the searching speed for qualified sensor nodes for coverage much higher than that of EPDM and ECAPM, making it easier to solve the coverage problem. And although EPDM adopts clustering technology, it uses intensive coverage that can find the optimal coverage subset only after searching all the nodes in the sensor node set at the time of energy conversion between nodes.

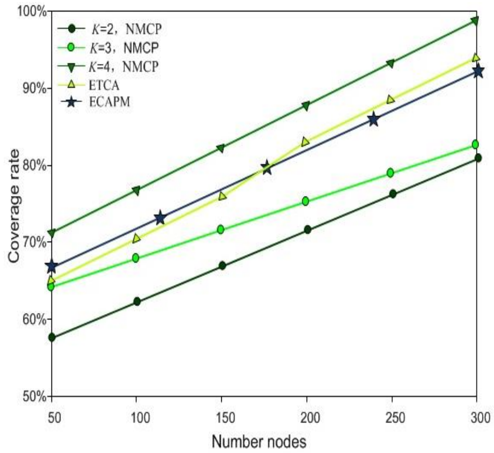

Fig.5 Comparison of Coverage Rate Changes

In simulating the coverage rate, the experiment is conducted on EPDM and ECAPM for comparison with the monitoring area as 200*200m^2. Figure 5 shows as sensor nodes increase, the coverage rates of the three algorithms increase accordingly. The coverage rate of 99.9% realizes the comprehensive coverage of the target nodes. If the number of active nodes is 50 and k=4, the coverage rate of NMCP is 71% while that of EPDM and ECAPM are 64% and 65% respectively. When the coverage rate reaches 99.9%, the number of active nodes of NMCP is 296. When the number of active nodes based on EPDM and ECAPM are both 296, the coverage rates of the two are 91% and 88% respectively. Thus, in this paper, the coverage rate of NMCP is 10.31% and 12.47% higher than that of EPDM and ECAPM respectively on the average.

6 Conclusions

Based on the analysis of problems and shortages in WSN coverage, this paper proposes a nonlinear multiple-target *K*-coverage protocol; then the network model is established and subordination relation between sensor nodes and target nodes is presented; next the paper calculates and proves the coverage rate of sensor nodes in the monitoring area and the expected value, and embodies the process to solve the coverage rate of any target node by senor nodes in the two-dimensional plane. In terms of node energy, this paper testifies the relation between communication distance and the maximum distortion value, as well as the process to realize NMCP protocol. For the last part, simulation experiments are made to testify the validity and feasibility of NMCP protocol.

Further researches will focus on how to effectively cover the edge of the monitoring area and irregular monitoring area.

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