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CFM: A FITNESS-MODEL-BASED TOPOLOGY CONTROL ALGORITHM FOR WIRELESS SENSOR NETWORKS

Linfeng Liu[1,2], Jiagao Wu[1,2], Fu Xiao[1,2], Ruchuan Wang[1,2]

[1] School of Computer

Nanjing University of Posts and Telecommunications

Nanjing, China

[2] Jiangsu High Technology Research Key Laboratory for Wireless Sensor Networks

Nanjing, China

Email: liulinfeng@gmail.com

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Abstract The main objective of wireless sensor network design is to maximize network lifetime. The network topology, which is the important foundation of upper layer protocols, serves as the supportive groundwork for this goal. We constructed the model of sensor networks, and investigated the property of topology with complex network theory. Three statistical parameters were used to describe the network structure, and then some ideal characteristics were concluded for topology. The characteristics of topology can be achieved by fitness model, so we designed an approximate clustering algorithm based on fitness model, which is distributed. CFM is composed of three phases: links generation phase, heads selection phase and cluster division phase. The performance of CFM algorithm was analyzed

through simulation experiments, which indicated a well-constructed topology and effectively prolonged network lifetime.

Index terms: Wireless sensor networks, topology control, fitness model, cluster-heads selection.

I. INTRODUCTION

Randomly distributed in the observed field and its vicinity, large numbers of sensors cooperate with one another through self-organized telecommunication, with wireless sensor networks (WSN) [1,2,3] making up. Data gathered by sensors are routed hop-by-hop to the sink, thus achieving the goal of observing and controlling the external physical world. Compared to traditional ad-hoc networks, the WSN is mostly intended for inhospitable environments, where persistent and continuous energy supply is lacking. Therefore, the main objective of WSN design is to prolong network lifetime by balanced and effective energy consumption. In the literature, WSN lifetime [4] has often been defined as the time for the first node to die in the course of routing due to battery exhaustion. Network topology, as the important foundation of upper layer protocols, not only improves the performance of routing protocols and MAC protocols, which is the main objective of WSN, but also serves as the supportive groundwork for implementation techniques in synchronization, data aggregation and object localization. Hierarchical topology control [5,6,7] is suitable for the management of large scale WSN. Because of pointless energy consumption by idle sensors in the network, clustering mechanisms are devised to maintain a network backbone for processing, forwarding data packets as well as shutting down the communication module of idle, non-backbone nodes so as to save energy.

This paper applies complex theory to describe the statistical characteristic of WSNs firstly, and the ideal topology formation is studied according to these statistical characteristics. Finally, fitness model is used to generate the topology. The remainder of this paper is organized as follows: Section II describes the WSN model and defines some concepts; Section III proposes an approximate topology control algorithm CFM (Clustering algorithm based on Fitness Model); Section IV provides the CFM analysis from the aspects of time complexity, energy consumption and ideal lifetime; Section V discusses the performance evaluation of CFM; and Section VI provides the conclusions.

II. NETWORK MODEL

A. Model Description

WSN topology is denoted as an undirected graph $G(V,E)$ in a two-dimensional plane, where V and E denote the set of sensors and links, respectively. $E \subseteq V \times V$, $|V|=N$, $|E|=M$. For any node $i \in V$, the current energy level is $e(i)$. All nodes have the same maximum transmitting power level p_{max}. When nodes are transmitting at p_{max}, they can cover a circular area of radius r_{max}. $G(V,E)$ is partitioned into k clusters C_1, C_2,…, C_k, where the cluster set $C=\cup C_i$. The cluster-head of C_i is denoted by c_i. To simplify the analysis and description of our model, we present the following assumptions:

***Assumption* 1.** Each node is aware of its location as well as its neighbors;

***Assumption* 2.** The ordinary node can only communicate with the cluster-head to which it belongs, and the cluster-head can only communicate with the neighboring cluster-heads or the ordinary nodes in its own cluster;

***Assumption* 3.** the cost function of link (i,j) is $w_{ij}=\omega d(i,j)^{\alpha}$ $(2\leq\alpha\leq6)$.

B Statistical parameters

Assuming uniform distribution of nodes, for any node i, the expectation distance (when θ=1) between i and its neighbors is expressed as

$$u(\theta)=\frac{4}{\pi r^2}\int_0^r\int_0^{\sqrt{r^2-x^2}}(x^2+y^2)^{\frac{\theta}{2}}\,\mathrm{d}y\mathrm{d}x \qquad (1)$$

where $r=[(<k>+1)A/\pi N]^{½}$, three statistical parameters are defined as follows.

1) Average path cost *T*

Average path cost T is defined as the average distance between any two nodes.

$$\begin{aligned} T &= 2\sum_{i\geq j} t(i,j)\,/N(N\text{-}1) \\ &= 2u(\alpha)\sum_{i\geq j} hop(i,j)\,/N(N\text{-}1) \end{aligned}$$

$$=u(\alpha)L \qquad (2)$$

where $t(i,j)=u(\alpha)hop(i,j)$, $L=2\sum_{i\geq j} hop(i,j)/N(N-1)$, and $hop(i,j)$ is the minimum hops in the path between i and j.

2) Average node degree <*k*> and distribution *P*(*k*)

In order to avoid high node degree causing heavy signal interference, $P(k)$ must satisfy $P(k)>P(k+1)$, and we consider $P(k)$ with power law distribution $P(k)\propto k^{-\gamma}$. $<k>$ can be defined as

$$<k>=\sum_{i\in V} degree(i)/N \qquad (3)$$

3) Clustering coefficient *C*

C is computed as Expression (4)

$$C=2\sum_{i\in V} E_i/<k>(<k>-1) \qquad (4)$$

where E_i is the number of links among the neighbors of node i. For any link (i,j), suppose (i,j) belongs to $\Delta(i,j)$ triangles, it is obvious that $\sum_{i\in V} E_i = \sum_{i\geq j}\Delta(i,j)$.

***Theorem* 1.** C is proportional to $<k>$ approximately.

***Proof*:** In Figure 1, nodes h_u and f_v denote the opposite ends of nodes i and j respectively. The probability of node p becoming the opposite ends of nodes i and j simultaneously is $P(i,j)$, and $P(i,j) = \left(\frac{C_{N-3}^{<k>-2}}{C_{N-2}^{<k>-1}}\right)^2 = \left(\frac{<k>-1}{N-2}\right)^2$. Therefore, mathematical expectation of $\Delta(i,j)$ $\mathbf{E}(\Delta(i,j))=(N-2)P(i,j)=(<k>-1)^2/(N-2)$, and C can be rewritten as

$$\begin{aligned} C &= 2\sum_{i\in V} E_i/<k>(<k>-1) \\ &= 2\sum_{i\geq j}\Delta(i,j)/<k>(<k>-1) \\ &= 2M\mathrm{E}(\Delta(i,j))/<k>(<k>-1) \\ &= 2\left\lfloor \frac{N<k>}{2} \right\rfloor (<k>-1)^2/(N-2)<k>(<k>-1) \\ &\approx N<k>/(N-2) \qquad (5) \end{aligned}$$

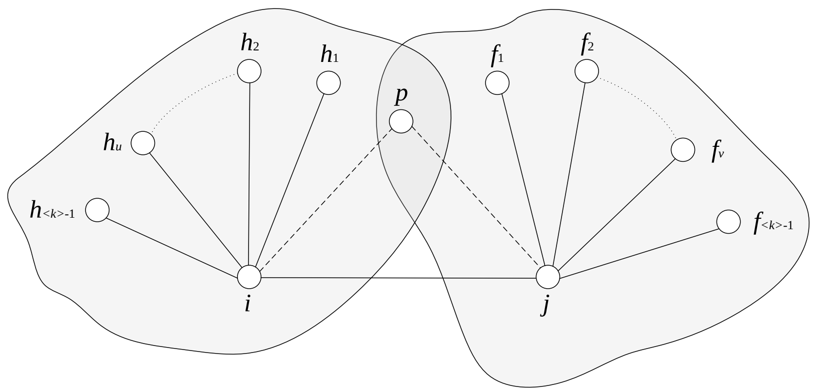


Figure 1. Node connection diagram

C Topology objectives

By Ref. [8] and the definitions of statistical parameters, some conclusions can be drawn as follows:

(1) **Network capacity**. The minimum distance between senders and receivers which are out of signal interference is denoted as $Range=u(1)(1+\Delta)$, then the throughput of single node φ must satisfy $\varphi \le \frac{16AW}{\pi\Delta^2 NLu(1)}$, where W indicates the largest data transfer rate. Therefore, the reduction of $<k>$ will enlarge the network capacity, namely, clustering coefficient C is inversely proportional to the network capacity.

(2) **Energy consumption**. The average energy consumption of paths is expressed as $\omega u(1)^{\alpha-1}L$, so the reduction of C or L will give rise to the decrease of energy consumption.

(3) **Communication interference**. The interference triggered by a single communication path can be defined as $L<k>/u(1)$, hence the reduction of C or L will alleviate the communication interference between nodes.

In brief, the decrease of C and L will lead to the increase of network capacity, the reduction of energy consumption, and the improvement of communication interference. As a result, the topology control objectives of WSN can be presented as

***Objective* 1.** Topology is fully connected, and the links are bidirectional;

***Objective* 2.** For any k, $P(k)>P(k+1)$;

***Objective* 3.** Min C;

***Objective* 4.** Min T;

III. ALGORITHM

Fitness model [9,10,11] was proposed by Bianconi and Barabási in 2001 [12]. Firstly, the constructing process of a fitness network is given as follows,

(1) **Increase**. Suppose the process begins with the network with m_0 nodes. At every round, a new node will be introduced to connect with m nodes in network, and the fitness of nodes obeys the probability distribution $\rho(\eta)$.

(2) **Priority connection**. The connection probability between the new node and the existing node i is denoted as Π_i, one has $\Pi_i = \frac{\eta_i k_i}{\sum_j \eta_j k_j}$, where k_i is degree of node i.

In this paper, we put forward an approximate topology control algorithm CFM (Clustering algorithm based on Fitness Model), which is composed of three phases: LGP (Links Generation Phase), HSP (Heads Selection Phase), and CDP (Cluster Division Phase). In LGP, nodes join the network according to fitness model; In HSP, the nodes with higher degrees will have the priority to becoming cluster-heads; In CDP, every ordinary node belongs to proper cluster-head, respectively. To facilitate the description of CFM algorithm, some definitions are given firstly,

***Definition* 1.** Links symmetry. For any link (i,j), there must be (j,i).

***Definition* 2.** Coverage area. For any nodes set S, whose coverage area is defined as cover(S)=$\{\cup$ neighbor_set $(i) | \, i \in S\}$, where neighbor_set $(i)=\{j | \, d(i,j) \le r_{max}\}$.

***Definition* 3.** Reachability in clusters. If in cluster C_i, for any $l \in V_i$, there is $d(l,c_i) \le r_{max}$, then C_i has reachability.

***Definition* 4.** Connectivity between cluster-heads. For any $i,j \le k$, there must be paths such as $(c_i, c_l, \ldots, c_l', c_j)$ between c_i and c_j.

The following are the description of the CFM algorithm:

A LGP

There are two kinds of messages in LGP: awake_msg and reply_msg (Figure 2). For any node, it should execute according to Step 1 to Step 5.

***Step* 1.** If node n hasn't joined WSN, and it receives the first awake_msg. Node n should determine m neighbors ($end(1), end(2)...end(m)$) in accordance with the preferential link probability, which is computed as

$$P_{\text{link}}(n,i)=\frac{\eta(n,i)k_i}{\sum_j \eta(n,j)k_j} \qquad (6)$$

where k_i and k_j denote the degree of node i and j respectively, and $\eta(n,i)$ denotes the fitness value from n to i.

$$\eta(n,i)=\{\frac{e(n)e(i)}{(e(n)^{\zeta}+e(i)^{\zeta})^{\frac{1}{\zeta}}}\}^{\beta}/d(n,i)^{\lambda} \qquad (7)$$

where β, λ, ζ are predefined parameters.

***Step* 2.** The determined neighbors form a list neighbor_set. Node n joins WSN and sets its power $p(n)$=Max$\{p(n,end(l))|1\leq l\leq m\}$, then returns a reply_msg to every node in its neighbor_set. Subsequently, n broadcasts an awake_msg with p_{max}.

***Step* 3.** If node i hasn't joined WSN, and it receives a reply_msg, it will abandon the message.

***Step* 4.** The node i in WSN receives a reply_msg, the sending node will be added into neighbor_set, and i will update its power $p(i)$=Max$\{ p(i,l)| l\in$ neighbor_set$\}$

***Step* 5.** If node i has joined WSN, and it receives an awake_msg, it will abandon the message.

Message Information	Node Information					Neighbor Information	
Type	ID	Position	Energy	Degree	InWSN	Neighbor Set	Degree

Figure 2. Structures of awake_msg and reply_msg

The maintained information of nodes includes: power, attachable neighboring set, and the degrees of neighboring nodes. The state transition diagram of LGP is depicted as Figure 3, and Theorems 2 and 3 can be deduced by LGP.

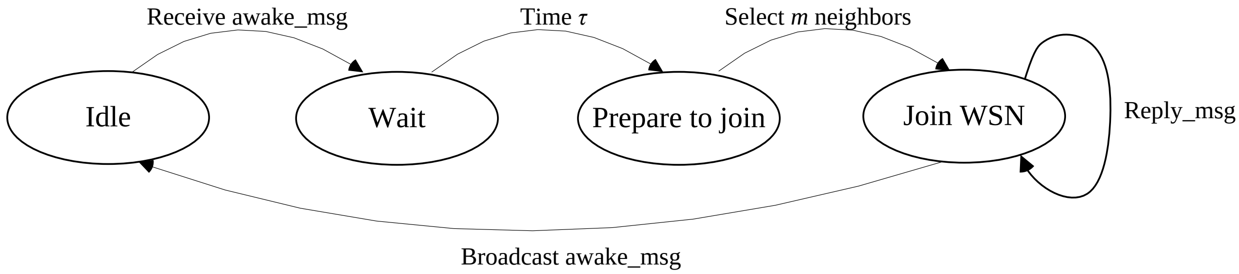


Figure 3. State transition diagram of LGP

Algorithm 1. Pseudo code of LGP:

```
LGP(G(V,E))
{ sink->broadcast(awake_msg);
while(∃ i∈V & join(i)= =0)
{ if( receive(awake_msg))
 { if(join= =0)
  { wait(τ);
   select(end[m-1]);
   add(end[m-1], neighbor_set);
   send(reply_msg); broadcast(awake_msg); }
   else
   { discard(awake_msg); }
  } else ( receive(reply_msg))
   { if(join= =0)
    { discard(reply_msg);}
     else
    { add(neighbor_set);}
} } }
```

***Theorem* 2.** After LGP, all links are symmetrical.

***Proof*:** Assume there is a link (i,j), then there are two cases for the emergence of this link: (1) node i receives the awake_msg from node j, and i is selected as one of the m ends, so it is certain j receive the reply_msg from i, subsequently, i will be added into the neighbors set of j, which brings the link (j,i); (2) node i receives the reply_msg from node j, then i has been the end of j obviously, so there must be (j,i).

***Theorem* 3.** If m is large enough, the network generated by LGP is connected.

***Proof*:** Suppose the extreme case m=N-1, any new node will connect with all nodes in the range of radius r_{max}, which is consistent with the case all nodes communicate with r_{max}. According to the assumptions, the network generated by LGP is connected.

B HSP

The start node of HSP is the sink as well. The sink join the cluster-head set, and send an initial_msg to the next cluster-head, which is selected by the coverage area produced by current cluster-heads. The next cluster-head is selected as Expression (8).

$$Cluster\text{-}head_{\mathrm{next}}=\{\, i \mid \mathrm{Max}\{\, degree(i) \mid i\in (\mathrm{cover}(S_{\text{cluster-head}})-S_{\text{cluster-head}})\,\}\}\qquad(8)$$

$S_{\text{cluster-head}}$ is current cluster-head set, cover($S_{\text{cluster-head}}$) is the nodes which can be covered by at least one of the nodes in $S_{\text{cluster-head}}$.

***Step* 6.** $Cluster\text{-}head_{\mathrm{next}}$ is selected by the current cluster-head, and then an initial_msg will be sent from current cluster-head to $Cluster\text{-}head_{\mathrm{next}}$.

***Step* 7.** If node i receives an initial_msg, it will judge that whether all nodes can be covered by cluster-head set. In that case, HSP terminates, and if not HSP continues to find the next cluster-head.

Algorithm 1. Pseudo code of HSP:

```
1.    HSP (G(V,E))
2.    { S_cluster-head={ sink };
3.      while (∃ v∈ V and v∉ cover(S_cluster-head))
4.      { while(i∈ S_cluster-head)
5.        { while(j∈ neighbor_set(i))
```

{ if ($degree(j)>degree$)
{ $degree=degree(j)$;
$node_{temp}=j$; }
} }
$node_{max}= node_{temp}$;
$S_{\text{cluster-head}}= S_{\text{cluster-head}} \cup \{ node_{max} \}$; }
output $S_{\text{cluster-head}}$; }

***Theorem* 4.** After HSP, any ordinary node has at least one cluster-head, and the topology has the connectivity between cluster-heads

***Proof*:** It is easy to be proven by the description of HSP.

C CDP

In CDP, the determined cluster-heads broadcast a notice_msg with maximum power, and ordinary nodes select cluster-head by the received strength of signal.

***Step* 8.** Every node in $S_{\text{cluster-head}}$ broadcasts a notice_msg, whose receivers will determine their nearest cluster-head by signal strength.

***Theorem* 5.** After CDP, the topology acquires reachability in clusters.

***Proof*:** For any cluster C_i, there will be some node $j \in C_i$, and $d(c_i, j)>r_{max}$. The cluster-heads set in CDP can cover all nodes, then there is some cluster-head c_l satisfies $d(c_l, j)\leq r_{max}$, therefore $d(c_i, j)> d(c_l, j)$, which contradicts the process of CDP.

IV. ANALYSIS

A Time complexity

The time complexity of CFM is consisted of three phases: the complexity of LGP is related with the number of nodes, that is O(N); when every cluster-head has one reversion process the worst complexity of HSP O(N^2) will be reached; the complexity of CDP is O(N). Therefore, the worst time complexity of CFM is O(N^2).

B Energy consumption and lifetime

According to Refs. [13,14], K~O(log$N$). Suppose all nodes own the same initial energy, which is denoted as *energy*. Every ordinary node collects interest data with probability p, and sends data to sinks with data rate v. The area of $G(V,E)$ is A. Every cluster is taken as a square (length of a side is $D=\sqrt{A/K}$), approximatively. The monitoring consumption of cluster-head at unit time is marked as *listen_cost*. The total consumption at unit time includes: the communications consumption in clusters e_{innerC}, the communications consumption of backbone e_{interC}, and the monitoring consumption e_{listen}.

The mathematical expectation of e_{innerC} is expressed as

$$\mathrm{E}(e_{\text{innerC}}) = Npv\omega \mathrm{E}(d_{\text{inner}}^{\alpha}) \qquad (9)$$

where $\mathrm{E}(d_{\text{inner}}^{\alpha})$ indicates the α-th power of distance between ordinary nodes and their cluster-heads, and $\mathrm{E}(d_{\text{inner}}^{\alpha})$ is computed as

$$\mathrm{E}(d_{\text{inner}}^{\alpha}) = (1/D^4)\int_{-D/2}^{D/2}\int_{-D/2}^{D/2}\int_{-D/2}^{D/2}\int_{-D/2}^{D/2}[(x_2-x_1)^2+(y_2-y_1)^2]^{\alpha/2}\mathrm{d}x_1\mathrm{d}y_1\mathrm{d}x_2\mathrm{d}y_2 \qquad (10)$$

The mathematical expectation of e_{interC} is

$$\mathrm{E}(e_{\text{interC}}) = Npv\mathrm{E}(\text{hop})\omega \mathrm{E}(d_{\text{inter}}^{\alpha}) \qquad (11)$$

where E(hop) is the mathematical expectation of hops from source nodes to sinks, and $\mathrm{E}(d_{\text{inter}}^{\alpha})$ is the mathematical expectation of α-th power of distance between neighboring cluster-heads. E(hop) is coputed as the sum of hops at horizontal ordinate (X_{hop}) and longitudinal coordinates (Y_{hop}). One get

$$\mathrm{E}(\text{hop}) = \frac{2}{K}\sum_{X_1,X_2=1}^{\sqrt{K}}|X_1-X_2| \qquad (12)$$

$\mathrm{E}(d_{\text{inter}}^{\alpha})$ can be expressed as

$$\mathrm{E}(d_{\text{inter}}^{\alpha}) = (1/D^4)\int_0^D\int_{-D}^{0}\int_0^D\int_0^D[(x_2-x_1)^2+(y_2-y_1)^2]^{\alpha/2}\mathrm{d}x_1\mathrm{d}y_1\mathrm{d}x_2\mathrm{d}y_2 \qquad (13)$$

Therefore, the total consumption at unit time $\mathrm{E}(e_{\text{total}})=\mathrm{E}(e_{\text{innerC}})+\mathrm{E}(e_{\text{interC}})+\mathrm{E}(e_{\text{listen}})$. Supposing that $\alpha=2$, one has $\mathrm{E}(d_{\text{inner}}^{\alpha})=D^2/3$ and $\mathrm{E}(d_{\text{inter}}^{\alpha})=4D^2/3$, then $\mathrm{E}(e_{\text{total}})$ can be written as

$$\mathrm{E}(e_{\text{total}}) = Npv\omega(D^2/3+8(\sqrt{K}-\frac{1}{\sqrt{K}})D^2/9)+K\,listen\_cost \qquad (14)$$

Thus, the ideal lifetime can be expressed as

$$\mathrm{E}(T_{\text{ideal}}) = N\,energy/\mathrm{E}(e_{\text{total}}) \qquad (15)$$

Hence, ideal lifetime is conversely proportional to p, v and *listen_cost*. The relation between N and lifetime can also be obtained from Expression (15): (**i**) if interest data is very low, K*listen_cost* will play the leading role in total consumption, under this circumstance one has

$$E(T_{\text{ideal}}) \approx Nenergy/Klisten\_cost \qquad (16)$$

Let $K = c\log N$, then $E(T_{\text{ideal}}) \approx Nenergy/c\log N$. Because the derivative of $E(T_{\text{ideal}})$ satisfies

$$\frac{dE(T_{\text{ideal}})}{dN} = (energy/c)\left(\frac{\log N - 1}{(\log N)^2}\right) > 0 \qquad (17)$$

The lifetime is proportinal to the number of nodes; (ii) Conversely, if interest data is very large, and the monitoring consumption can be ingored. One obtains

$$E(T_{\text{ideal}}) \approx 9NenergyK/Npv\omega A[3+8(K^{1/2}-K^{-1/2})] \qquad (18)$$

Therefore, at this case the lifetime is inversely proportinal to the number of nodes

V. PERFORMANCE VALUE

CFM is evaluated by observing the performance variation when adopting different model parameters and by comparing CFM with other algorithms. CFM is realized in OMNeT++ [15]. MAC Layer and routing are outside the scope of this paper. The IEEE 802.15.4 routing algorithm [16] is adopted for MAC and FA [17]. N nodes are deployed in the area 100m×100m, one sink node and pN source nodes are selected randomly. The values of the parameters are shown in Table 1.

Table 1: Simulation Parameters

Parameters	**Description**	**Value**
r_{max}	Maximum communication radius	20 m
ω	Parameter of cost formula	2×10^{-5} J/kB•m^2
e	Initial energy	*random*(9.5,10.5)
v	Generated rate of data flow	8 kbps
α	Exponent of cost formula	2
ζ	Predefined parameter	2

listen_cost	Energy consumption of monitoring	0.1 J
N	Number of nodes	100
p	Data detection probability	0.1
m	Number of selected neighbors	2
β	Predefined exponent	0.1
λ	Predefined exponent	0.4

A Influence of β and λ

The influence of β and λ on the WSN lifetime will be observed and analyzed in this simulation. In CFM, β and λ reflect the level of significance at node residual energy and link energy cost, respectively. Figure 4 illustrates lifetime will decrease first and ascend later as the increase of one exponent when the other is fixed, and the lifetime can be maximized when both β and λ are given appropriate value. In Figure 4, the maximum lifetime (about 108.6s) will be obtained at β=0.1 , λ=0.4.

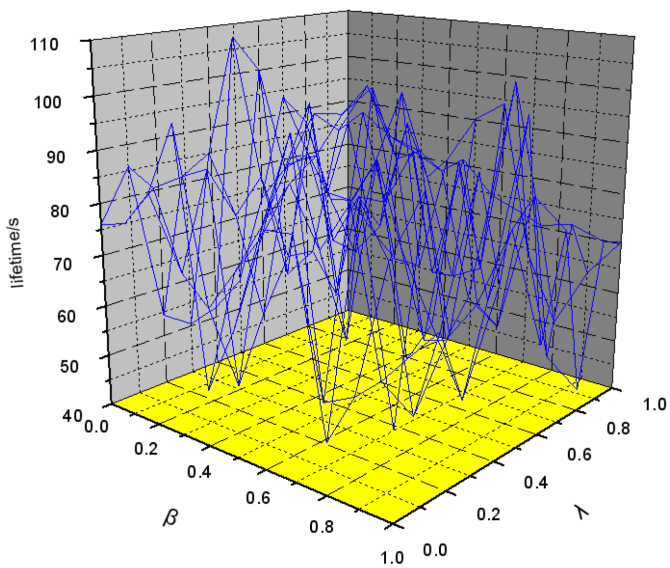


Figure 4. Influence of β and λ on the WSN lifetime

B Influence of p and v

The value of p varies from 0.06 to 0.1, WSN lifetime variation with N exhibits five plots shown in Figure 5. Shorter WSN lifetime will be obtained with higher values of p. This because that the increase of p makes the traffic load become heavier. Similarly, as shown in Figure 6, when p is determined the increase of v results in decrease of lifetime as well.

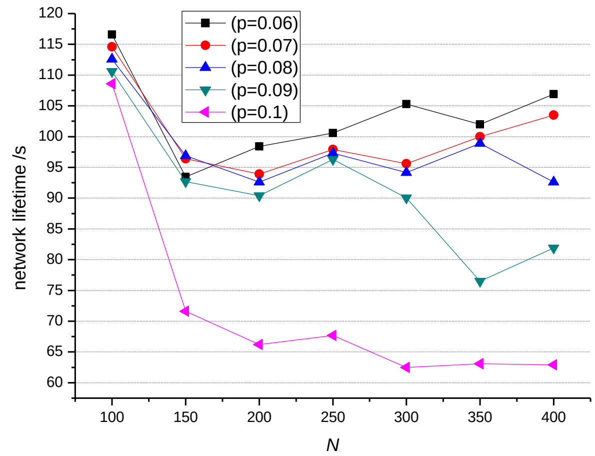


Figure 5. influence of p on the WSN lifetime

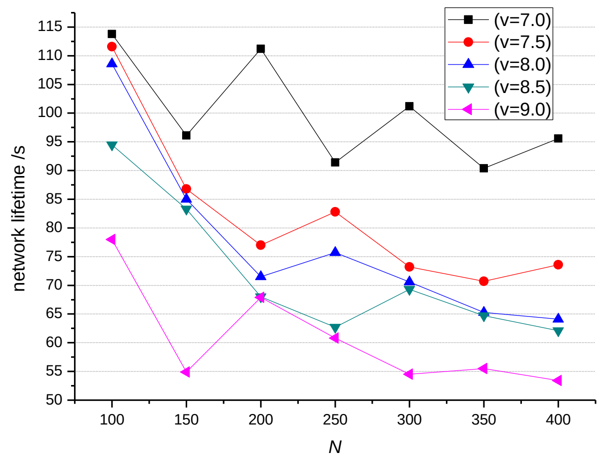


Figure 6. Influence of v on the WSN lifetime

C Influence of m and listen_cost

In Figure 7, the value of m is assigned as 1, 2, 3, and 4, the plot m=3 is higher than other plots because the small m implies WSN connectivity can not be guaranteed, and conversely, large m is prone to generate longer links between neighboring cluster-heads, which leads to the reduction of lifetime consequently. From Figure 8, WSN lifetime gradually reduces as *listen_cost* increases. Furthermore, the plots *listen_cost*=0.12 and *listen_cost*=0.14 are very close, because the influence of monitoring consumption will be significantly weaken when *listen_cost* is large enough.

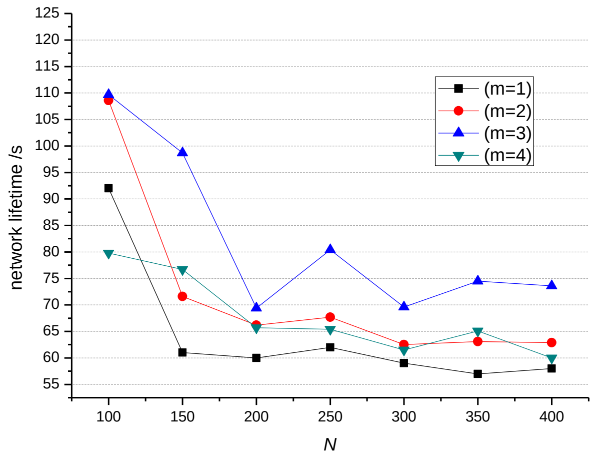


Figure 7. Influence of *m* on the WSN lifetime

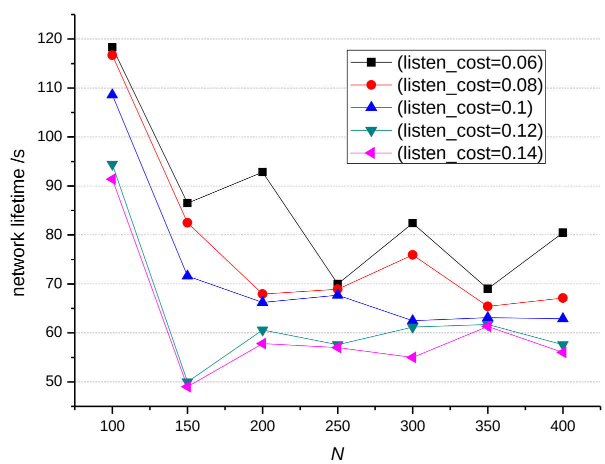
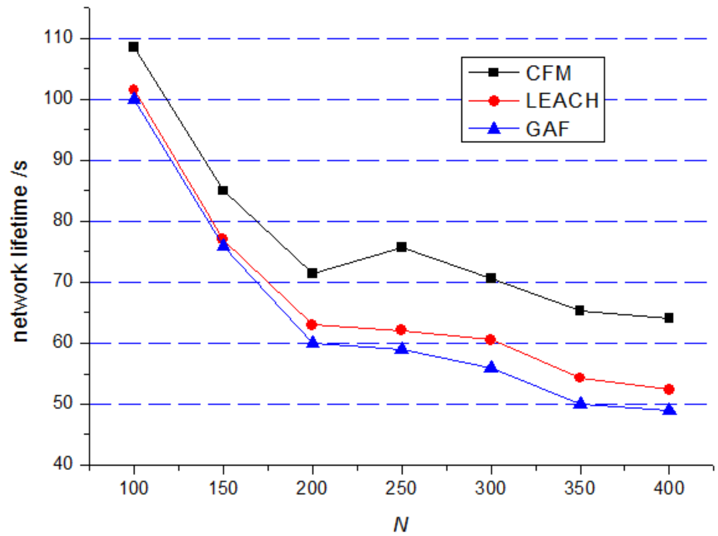


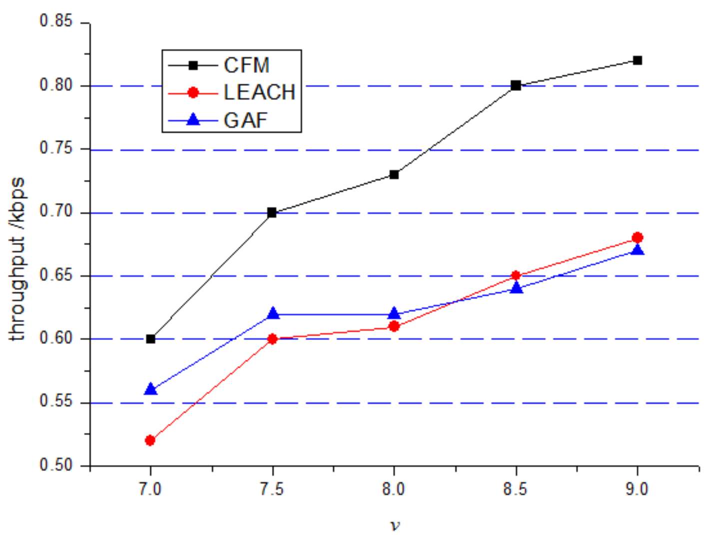
Fig. 8. Influence of *listen_cost* on the WSN lifetime

D Comparision with other algorithms

This simulation compares WSN lifetime and throughput in CFM, LEACH, and GAF. As shown in Figure 9, both CFM lifetime and throughput are apparently higher than those of LEACH and GAF, which is attributed to the fact that CFM is more concerned about energy consumption and network capacity. The differences of plots become more obvious as the increase of *N*, and the lifetime gap of CFM and GAF reaches 15.1s when *N*=400.



(a) Lifetime comparision



(b) Throughput comparision

Figure 9. Performance comparision of different algorithm

VI. CONCLUSIONS

In this paper, the problem of topology control in wireless sensor networks has been investigated by maximizing the WSN lifetime. Formal WSN model was constructed and a topology control algorithm based on fitness model was proposed. Simulation results suggest CFM can extend lifetime and improve throughput effectively. CFM performance will be influenced by the pre-defined parameters m, β, λ, ζ, so the self-adaption of algorithm [18] will be analyzed in the future. Moreover, WSNs are deployed in severe environment popularly, for instance, the node puts up mobility [19], the coverage area may be irregular, hence the improvement of CFM must be interrelated with the actual applications.

VII. ACKNOWLEDGMENTS

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