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Topology Optimization Control with Balanced Energy and Load in Underwater Acoustic Sensor Networks

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Abstract- In view of unbalanced link bandwidth and node energy consumption in Underwater Acoustic Sensor Networks (UASNs), a distributed topology optimization control algorithm (EL-BatCA) is proposed, which is based on balanced network energy and load. A hierarchical network model is designed based on minimum-hop, by which the nodes are divided into n layers. EL-BatCA is implemented through three stages-topology graph formation in initialization, an innovative transmission power adjustment in topology control, and finally topology optimization through object functions. Simulation results show that EL-BatCA not only balances energy consumption and network load, but also prolongs network lifetime and improves network throughout.

Index terms: UASNs; Network Load; Node energy; Topology Optimization; Topology control, EL-BatCA

I. INTRODUCTION

The application of Underwater Acoustic Sensor Networks (UASNs) in ocean exploitation and ocean military has wide application prospects, such as ocean monitoring, target detection, ocean disaster forecasting and alarm and so on, which promote the technology of UASNs to become a new research hot point[1]. UASNs consist of sensor nodes, AUV and surface base station, which communicate by acoustic signal. The surface base station can further connect with Internet, and then forms an interactive environment. They realize extracting real-time data from coverage areas of network and sending control messages to sensor nodes.

Due to the special environment of underwater applications, conventional communication media attenuate very fast under water, such as electromagnetic wave and optical signal, which are not suitable for long distance communication. So acoustic signal is commonly used in underwater communication, but comparing to terrestrial radio channel, acoustic channel has some disadvantageous features, for example, propagation delay is long; available link bandwidth is terribly decreased by multipath effect and Doppler frequency shift; maximal communication distance of acoustic signal is only a few tens of kilometers[2] due to reflection and refraction of acoustic signal; also the salinity, temperature, depth of water, fish and ocean currents all have impacts on the transmission of acoustic signal; besides the battery usually cannot be replaced after sensor nodes are deployed, and solar cells cannot be used in deep waters, UASNs is faced with a huge challenge of limited energy supply in long term monitoring. For the aforementioned reasons, research on how to save node energy and fairly distribute link bandwidth cannot be neglected in UASNs. Topology control is one of important techniques in energy-saving of UASNs, it can adjust the transmission power of every node to reduce the number of neighbors, which can save node energy, accordingly prolong battery life. And it also can remove redundant paths, to simplify network topology and reduce channel collisions.

Therefore, we propose a distributed topology optimization control algorithm (EL-BatCA) with balanced node energy and network load in 3D UASNs. The main idea of EL-BatCA is that sensor nodes choose relay nodes by adjusting their transmission power, which is based on the number of neighbors in the next layer; and then determine a relay node after topology optimization, which is based on residual node energy and available link bandwidth.

The rest of this paper is as follows. Section 2 presents some related works, section 3 describes network model, section 4 introduces the topology optimization control algorithm in detail, section 5 analyzes the simulation results, and finally in section 6, we conclude our paper and future work.

II. RELATED WORKS

Topology control mainly discusses the problems of eliminating unnecessary communication links to form an optimized network structure for data transmission. It is based on power control and selection of backbone nodes while satisfying network coverage and connectivity. At present, there are many categories of topology control methods in Wireless Sensor Networks (WSNs), such as research direction, algorithm implementation. This paper is grounded on the latter, which can also be divided in two methods: centralized topology control algorithm and distributed topology control algorithm.

Much work has be done on topology control algorithms, such as Relative Neighborhood Graph (RNG) algorithm[4], Minimum Spanning Tree (MST) algorithm[6], Connect algorithm, but they are centralized topology control algorithms[5], not suitable for application in UASNs. Besides, there are some distributed topology control algorithms, for example, Local Information No Topology (LINT) algorithm [5], LILT algorithm [5], distributed relative neighborhood graph (dist-RNG) algorithm [10], Local Minimum Spanning Tree (LMST) algorithm[11], Mobile Grid algorithm[7], Common Power Level (COMPOW) algorithm[8]. Although these algorithms are applied in UASNs, they don’t consider balanced characteristics of energy depletion and network bandwidth.

Jaromczyk J W and Toussaint G T [4] present RNG algorithm, in which the basic principle of choosing a path is distance between two nodes. Oleksandr Grygorash and Yan Zhou [6] design MST algorithm using Kruskal or Prim algorithm to realize a connected topology structure with minimum sum of transmission power. Ramanathan R and Rosales-hain R [5] propose Connect algorithm, it combines all connected subgraphs into a full connected graph by is a simple greedy algorithm. The three algorithms are all based on global position information. But it is very difficult for us to obtain node information underwater, so these algorithms are not fit for UASNs.

Ramanathan R and Rosales-hain R [5] discuss LINT algorithm, in which neighbor number of each node has the highest limit N_h and lowest limit N_l. If the number of neighbors is more than N_h, it will reduce transmission power, and if the number of neighbors is less than N_l, it will increase transmission power. LIU J and LI B [5] present LILT algorithm, it uses global information of link state to adjust transmission power of node in time, which finally forms a network with the minimum price of link weight. Li N and Hou J C [10] advance DRNG algorithm, it builds a neighbor node set based on a principle to adjust its transmission power. The principle is that: if there are more than one connected links among three nodes, the link with smallest weight will be reserved and the rest links will be removed. Li N and Hou J [11] present LMST algorithm, which independently builds a local minimum spanning tree based on reachable neighbor information, finally realizes a bidirectionally connected topology. It can efficiently reduce transmission power and maintain global connectivity, while neighbor number of every node is less than a settled value in order to relieve MAC collisions. U. S. Sutar and Shrikant K Bodhe [7] explores Mobile Grid algorithm, the main idea of it is that each node adjusts transmission power to create an optimal network competition index in mobile networks, and form a network topology with the maximum network capacity. Narayanaswamy S and Kawadia V [8] proposes COMPOW algorithm, which assumes transmission powers of all nodes are same in a homogeneous network topology and this transmission power is the minimum power satisfying network connectivity. LINT algorithm, DRNG algorithm, LMST algorithm and Mobile Grid algorithm can reduce node energy consumption, but they don't take the balance of node energy into account. LILT algorithm, Connect algorithm and COMPOW algorithm can lighten network load, but similarly they don't consider the balance of network load.

However, the research on topology optimization for UASNs is very little. F. Bendali and C. Duhamel [12] by means of finding an independent dominating connectivity set (IDC) to realize optimization. Katsalis Konstantinos and Xenakis Apostolos[13] propose an optimization method based on the electrical conductivity of soil to adjust topology structure for agriculture application. Xi Shi and Yangsheng Xu propose an Undetour optimization [14], it firstly finds out the shortest path between two nodes in the network, then uses Genetic Algorithm (GA) to choose the initial population. Xiucai Ye and Li Xu present an optimization method through comparing high clustering coefficient to remove some paths [15]. The research of UASNs about energy saving is mainly centered on network topology. The above literatures can select a path with the maximum residual energy, but they utilize two different methods: 1. nodes with high residual energy to relay data for network energy balance; 2. it minimizes the energy of transmitting information by unit. Their advantage is to avoid path with less energy and prolong the life time. Their defect is that they are centralized algorithm and the optimization scheme is from down-to-top with a single optimization condition.

Aiming at the defections of aforementioned algorithms, this paper proposes a distributed topology optimization control algorithm (EL-BatCA) with balanced node energy and network load. EL-BatCA has two characteristics: (1) Adopting distributed power control method, it decreases interfere between nodes, reduces energy consumption and realizes a network topology structure with effective data transmission. (2) Taking node energy consumption and network load as optimization target, it will generate a balanced network topology.

III. MODEL DEFINITION

We first design a hierarchical network model of UASNs, and then we use it to analyze node energy consumption in detail, link bandwidth occupation, and transmission power adjustment based on this model.

3.1 Hierarchical Network Model

It is assumed that all nodes are randomly deployed in an underwater cube as depicted in figure 1. The gateway is fixed at the center of surface and can obtain its location by GPS. Each node is assigned a unique ID and sends packets to the gateway through relaying nodes. The communication radius of nodes is fixed to R.

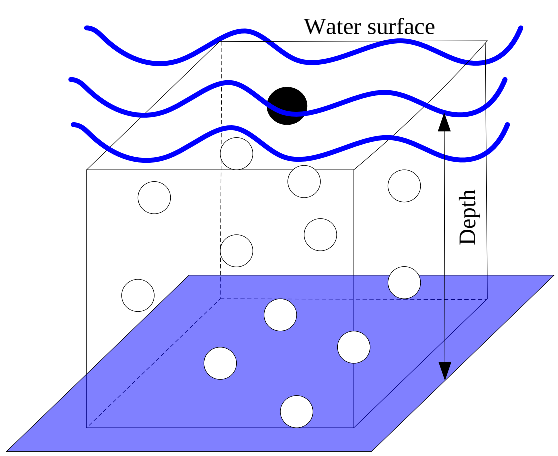
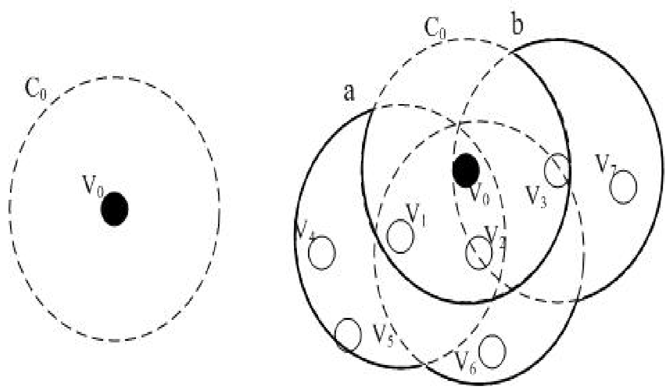


Figure 1. Network scenario

Because all nodes are deployed underwater, they are always floating. Compared to the gateway, it will pay a greater price to obtain their real-time locations than the gateway's. So we propose the concept of network hierarchy: the gateway obtains information of its neighbors through communication, as a corollary, each node can know the information of its neighbors. In view of this concept, this paper designs a top-down hierarchical network model: all nodes are divided into n layers based on minimum-hop, which is the least hop number from a node sending data to the gateway in figure 2. Solid dot and dash circle respectively represents the gateway and communication radius in figure 2(a). Hollow dot represents sensor node, V_1, V_2, V_3 are all in the communication radius of gateway, and they can communicate with it directly, so the minimum-hop is 1 and they are assigned to the 1st layer. Whereas V_4, V_5, V_6, V_7 in arc $\overset{\frown}{ab}$ are not in the communication radius of gateway, and they have to communicate indirectly through relay nodes such as V_1, V_2, V_3 in figure 2(b), so the minimum –hop is 2 and they belong to 2nd layer.



(a) (b)

Figure 2. Node hierarchical models

Let NL_i denote a set of nodes in the i-th layer, V_i represents node ID, especially V_0 is the gateway ID. We define $NL_0=\{V_0\}$, the nodes in the 1st layer belong to NL_1 but except the node which belongs to NL_0, so nodes in NL_i belong to the i-th layer and the minimum-hop of them is i. As illustrated in figure 2(b), $NL_1=\{V_1,V_2,V_3\}$, $NL_2=\{V_4,V_5,V_6\ ,\ V_7\}$ Therefore

$$NL_i=\{V_i \mid hop_{v_i}=i\} \quad \text{..........(1)}$$

In Eq.(1), hop_{v_i} denotes the least hops of V_i sending data to the gateway. Namely the layer to which V_i belong is equal to hop_{v_i} .

3.2 Energy Consumption

In UASNs, the loss of nodes energy embodies the following two main aspects [3]: firstly, nodes send data which is collected by itself to its last hop nodes, and this process will consume partial energy; secondly, nodes transmit data which is sent by their next hop nodes, and this process will consume more energy. However, if nodes send data at a certain transmission power, the energy consumption of nodes is not related with the communication distance. So we adopt the energy consumption model in topology optimization.

We assume each node has an initial energy reserve ε_0 (unit: J). Let N_{ij} be the number of neighbor nodes from the (i+1)-th layer of V_j belonging to NL_i, and E_{ij} be residual energy of V_j belonging to NL_i at interval t. It is supposed that each node consumes e_r and e_t to receive and transmit one bit respectively. Let g_v be the data generation rate (unit: bit/s).

The nodes belonging to NL_n only send data generated by them in figure 3(a). Therefore, the residual energy of nodes from this layer during the period of t is

$$E_{nj} = \varepsilon_0 - e_t * g_v * t \qquad (2)$$

The nodes belonging to NL_t (t≠n) have to receive and resend data transmitted by nodes in their next layers in figure 3(b). Therefore,

$$E_{ij} = \varepsilon_0 - N_{ij} * (e_r + e_t) * g_v * t - e_t * g_v * t \qquad (3)$$

From Eq. (3), we can see when N_{ij} decreases and E_{ij} increases.

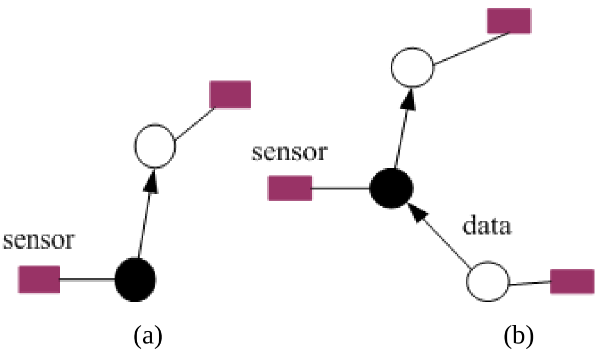


Figure 3. Node energy consumption model

3.3 Available Link Bandwidth

Assuming that each communication link has the same maximal channel capacity of C (unit: bps), let b_{ij} be link bandwidth needed for error-free data transmission from V_j to V_i . We define that g_v is bandwidth occupied by nodes when sending data. The nodes sending data occupy bandwidth from the last layer.

$$b_{ij} = g_v \quad \text{(4)}$$

Bandwidth occupation of the other layer can be depicted as

$$b_{ij} = N_{mj} * g_v \quad \text{(5)}$$

In Eq. (5) N_{mj} denotes the number of neighbors in NL_m of V_j which belong to NL_{m-1}, as illustrated in figure 4.We use B_{ij} to depict the available link bandwidth , Therefore

$$B_{ij} = C - b_{ij} \quad \text{(6)}$$

From Eq. (5) and Eq. (6), we can see that when N_{mj} decreases, b_{ij} decreases and B_{ij} increases.

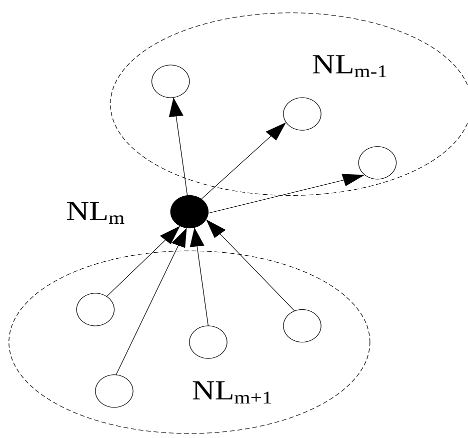


Figure 4. Model of Available Link bandwidth

3.4 Transmission Power Adjusting

Let P_{th} denote the reception sensitivity of a node, and x be the distance a packet transmitted from source node to gateway, A(x) be the distance attenuation of power[9], so the lowest node transmission power is $P_{th}/A(x)$. And physical quantity A(x) is related with transmission mode and frequency of information, so

$A(x)= x^k a^x$ ……………………………………………………………………………………… (7)

In Eq. (7), k is energy extension coefficient (k is 1 of cylindrical extension, but actual k is 1.5, k is 2 of spherical extension), a is absorption factor which depends on frequency.

If a node has k next relay nodes and received signal intensity of a packet is P_{rij}, we select the minimum transmission power P_{rij}, and $P_k=\min(P_{rij},\ldots,P_{rih})$,therefore

$P_{max}=P_k/A(x)$ …………………………… ……………………………………………………… (8)

If Pt is transmission power after adjustment. Then

$P_t=P_{th}/A(x)$ ……………………………………………………………………………………… (9)

From Eq. (8) and Eq. (9), we can obtain the equation below:

$P_t=P_{th}P_{max} / P_k$……………………………………………………………………………….... (10)

In Eq. (10), P_t is the final transmission power after topology control.

IV. TOPOLOGY OPTIMIZATION CONTROL ALGORITHM

In UASNs, the energy of nodes is generally battery-powered, and it is difficult to replace battery. However, the nodes on backbone path (more much load than others path) sometimes deplete energy faster and tend to die soon, which leads to link disconnection and short network life time.

The core idea of a topology optimization control algorithm with balanced network energy and load (EL-BatCA) for UASNs is that sensor nodes choose their relay nodes by adjusting their transmission power based on transmission power of neighbor nodes, and then determine a relay node to the gateway by topology optimization in light of residual node energy, available link bandwidth and edge-path. This algorithm mainly consists of the following there stages: (1) Topology structure initialization. (2) Topology control. (3) Topology optimization.

4.1 Topology Structure Initialization

The gateway sends “hello” at the beginning, if nodes receive the message firstly, those nodes belong to the 1st layer and NL_1 as mentioned in section 3.1, and they transmit “Hello” to other nodes; the nodes discard the message when they receive the message again, which have been divided into the 1st layer, otherwise, those nodes belong to the 2nd layer.. By analogy, all nodes are divided into n layers. Finally, it generates a topology graph. The implementation procedure of the topology structure initialization is illustrated in figure 5. In this stage, the gateway is not in any layers.

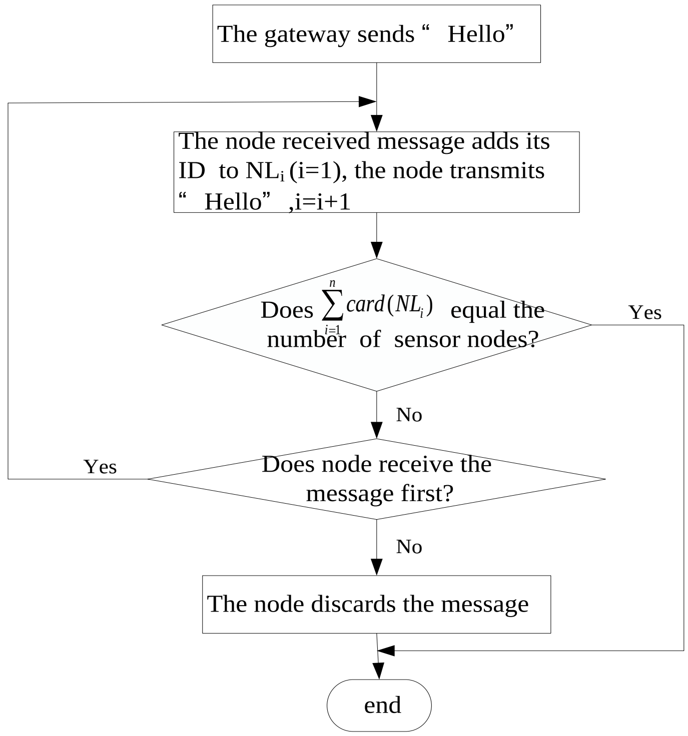


Figure 5. Flow of topology initialization

4.2 Topology Control

After topology is formed, for any node V_i ($V_i \in NL_i$) in network, except nodes belonging to NL_1(because they send message to the gateway directly), V_i first sends "hello" to its neighbors in NL_{i-1}, which answer "ACK" that includes signal intensity of receiving data packet P_{rij}. So V_i knows P_{rij} of every neighbor, and it chooses nodes with the minimum P_{rij} as relay nodes. Meanwhile it calculates its transmission power P_t through Eq. (11) mentioned in section 3.4, as is illustrated in figure 6.

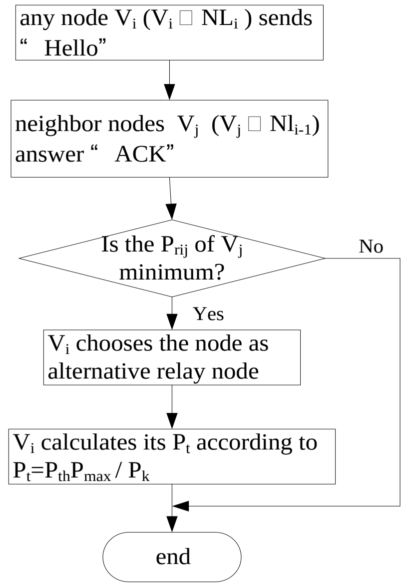


Figure 6. Flow of topology control

4.3 Topology Optimization

After topology control, most nodes have decreased their transmission power, but there are still redundant paths. So those paths will removed by topology optimization. Before demonstrating the optimization, we will define an object optimization function.

$$f(\mathrm{V}_i) = \min\left(\sum_{i=1}^{n}(\alpha E_i + \beta B_i)\right) \quad (12)$$

In Eq. (12), $\alpha$and$\beta$are important adjustment coefficients, and $\alpha+\beta=1$, we can adjust $\alpha$and$\beta$to actual applications. In this paper, we chooseαandβas 0.5, in order to emphasize that energy and bandwidth have the same importance.

The idea of topology optimization in this paper is based on the following three principles:

(1) According to the idea of hierarchical network previously stated in section 3.1, the optimization is from the 0-th layer to the n-th layer. That is to say, we optimize all the nodes in NL_1 firstly, then the nodes in $NL_2,\ldots,NL_n$,until the nodes in NL_n (n is changeable)have been optimized. That is because UASNs is not equipped with any infrastructure and it is not easy to get the whole network's information. This paper adopts a distributed topology optimization algorithm. It firstly optimizes the topology with known local information, and then based on the known optimized topology; it accomplishes the optimization of the rest network.

(2) Node energy depletion and link available bandwidth are taken as the primary constraint conditions of topology optimization. According to its residual energy and the available bandwidth, node chooses an optimal relay node as next hop for sending data to the gateway. In this way, we can ensure a balance of all nodes' residual energy and available link bandwidth in optimized network.

(3) If some nodes could not be optimized successfully by using the second principle, we will take edge-path as the final constraint condition and the edge-path mentioned here is mainly referred to the path in which there are fewer nodes sending data to the gateway. When nodes send data to the gateway, there is a situation that some paths passing through the gateway is heavily loaded while some paths are vacant. However, because all the nodes in network are disposed with equal energy, this situation will lead to high energy consumption on the main path. Moreover, choosing the nodes in edge-path as relay nodes will not only alleviate the network's load, but also decrease energy consumption.

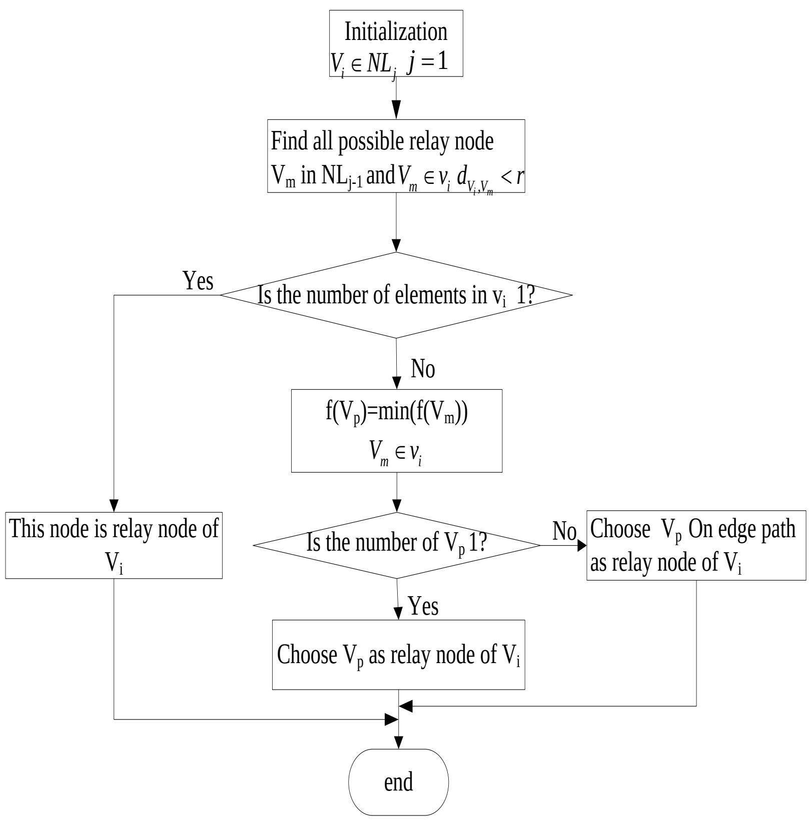


Figure 7. Flow of topological optimization

For any node V_i in NL_j , it firstly finds all possible relay nodes V_m in NL_{j-1}, if the number of relay node is 1, V_m is the relay node of V_i. Otherwise, choosing node with the largest object optimization function $f(V_i)$ as relay node. If the number of relay nodes is 1, this node is the relay node. If not, it can choose relay node through IfOnEdge (its value is 0 or 1) .Figure 7 shows the flow of the process of optimization.

V. PERFORMANCE EVALUATION

5.1Simulation Scenario and Parameter Settings

This paper simulates and contrasts the topology optimization control algorithms we proposed and LMST algorithm on throughout, network span life time and end-to-end delay. For corresponding with the general characteristics of application, we assume a 2D simulative scenario. And the parameters of the simulation are as follows: 59 nodes are randomly deployed in a square area, of which the edge length is 50km.The gateway is fixed on surface at the center of this area, and its coordinate is (25, 25). The maximum transmission power of nodes P_{max} is 900w, the maximum communication radius R_{max} is 30km, the receiving sensitivity P_{th} is 2w, transmission power p can be changed from 2w to 900w, the sampling period of topology restructure is 30s. It is assumed that the power consumption of receiving and transmitting one bit is 0.9w and 8w respectively. The initial energy and bandwidth of all nodes are assumed to be the same with ε_0=1188000J and B=9600bBps.

Then we set the parameter in sending a packet: the interval time of sending data packet is 1s, the length of data packet is 1024, the beginning time is 13s, and the end time is not limited.

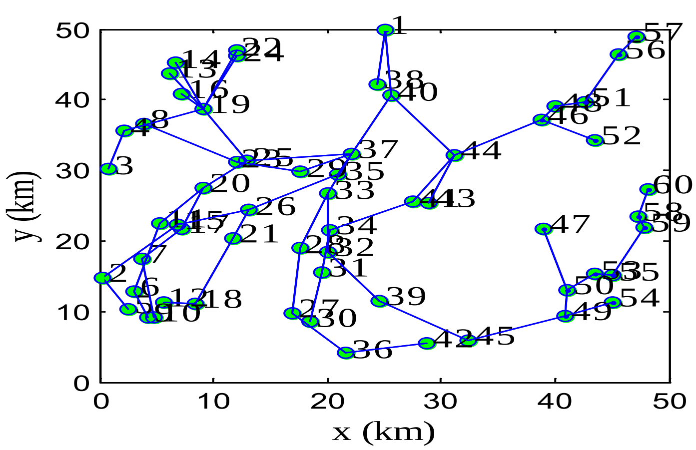


Figure8. Optimized Topology Tree

5.2 Performance Analysis and Simulation

We will analyze performance of the topology optimization control algorithm on network span time, throughout and end-to-end delay from two stages. Figure 8 is a topology tree after optimization control. From this figure, we can see number of every node is less than 4, and every node has only one relay node. So it realizes the balance of node residual energy and available link bandwidth.

Firstly, we evaluate the performance of topology control from the following four aspects.

(1) Network Throughout

We define network throughout as the ratio of the quantity of terminal data node receives to the time used of simulation, namely

Throughout (packets/sec) =the number of data packet unit time/ unit time.

Figure 9 shows the relation of four algorithms on throughout. Form this figure we can find that throughout is relevant to the number of valid nodes. That is because the number of valid nodes decides the amount of sending packet. Also we can see that LMST algorithm has the best throughout, the next is LMST algorithm and DRNG algorithm, the effect of COMPOW algorithm is the worst. But before 120s, LMST algorithm is better than EL-BatCA algorithm, at 120s, some nodes begin to die in LMST algorithm, DRNG algorithm and COMPOW algorithm. After 120s, EL-BatCA algorithm is better visibly on the throughout. So EL-BatCA algorithm guarantees the number of valid nodes in network life time is more than other algorithms.

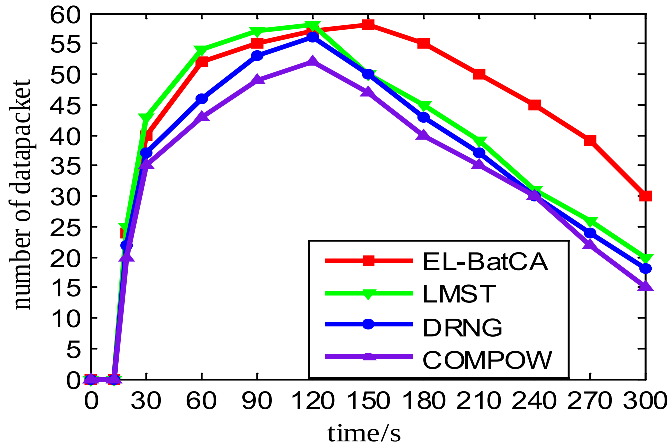


Figure 9. Curves of network throughout

Figure 10 and figure 11 show the relation between bandwidth and throughout respectively at g_v=400bit/s and g_v=1200bit/s. The two figures indicate that the lower data generated rate, the more high throughout, this is because every link bandwidth can satisfy bandwidth requirement of nodes when they send data at g_v=400bit/s, but some link bandwidth cannot do at g_v=1200bit/s, so nodes have to discard some packets selectively under this condition, and this possibly leads to throughout decreasement. It also can be seen that throughout greatly improves under different conditions of optimization, that is residual energy and available link bandwidth are better balanced in comparison with the single condition of optimization.

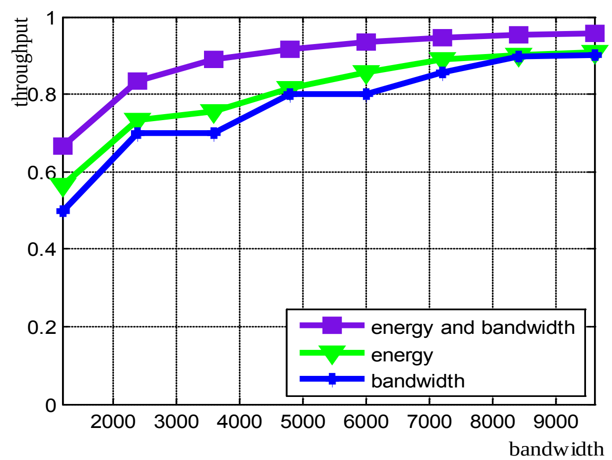


Figure10. Relation between throughout and bandwidth (g_v=400bit/s)

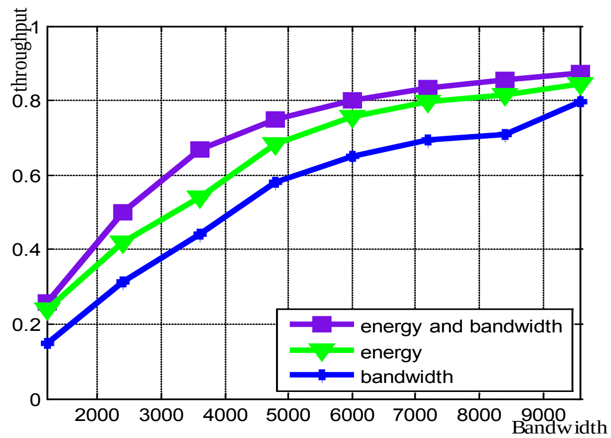


Figure 11. Relation between throughout and bandwidth (g_v=1200bit/s)

(2) Network Span Life Time

The definition of network span life time has many patterns. The basic principle is that network can hold the maximum amount of invalid nodes when maintaining effective communication. In this paper we define the network span life time as the time of network can normally work until the percent of died nodes is below 50%.

Figure 12 shows network span life time of four algorithms. In figure 12, DRNG algorithm has the highest speed of node energy consumption. The next is COMPOW algorithm and LMST algorithm. And EL-BaTCA has the slowest speed. Some nodes begin to die at about 155s in LMST algorithm, and the number of valid nodes drops below 50% at about 280s; some nodes begin to die at about 130s in COMPOW algorithm, and the number of valid nodes drops below 50% at about 260s; Some nodes begin to die at about 125s in DRNG algorithm, and the number of valid nodes drops below 50% at about 225s;however, Some nodes begin to die a at bout 215s in EL-BatCA algorithm, and the number of valid nodes drops below 50% at about 295s. It can be found that EL-BatCA algorithm can keep a long work time and prolong network span life time.

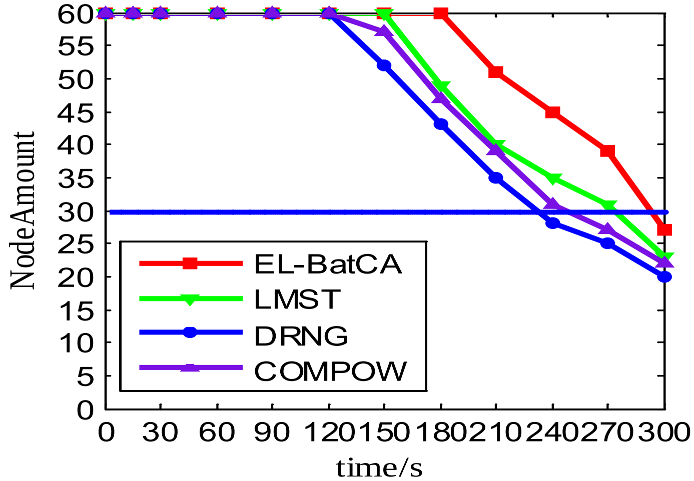


Figure12. Curves of network span life time

From Figure 13 and Figure 14, we can see network span life time is greatly improved than that before optimization, and the proportion of improved network span life time is different at different data generation rate. Because available bandwidth of some links do not meet the requirement when nodes transimit data during the period of t. For the sake of reliable data transmission, we adopt delay time retransmission mechanism; this method leads to greatly energy consumption of nodes, accelerates the rate of nodes dying, and shortens network span life time.

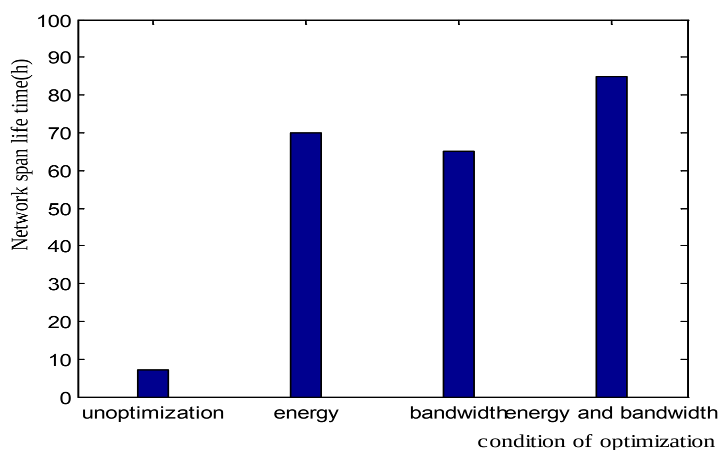


Figure13. Network span life time of different optimization conditions (g_v=400bit/s)

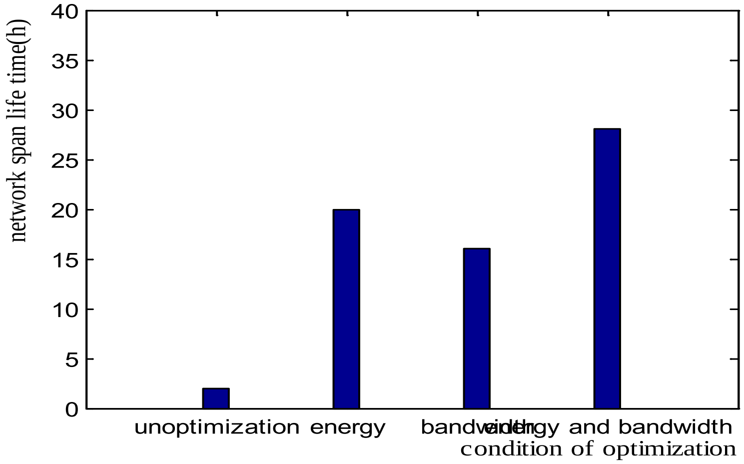


Figure14. Network span life time of different optimization conditions (g_v=1200bit/s)

(3) Node Residual Energy

We define the residual enery as available energy for working a period of a node.

Figure 15 and figure 16 show the residual energy of nodes. It is denoted that residual energy is related with the number of neighbors. The more neighbors, the less residual energy. After optimization, we ensure that the neighbor number of each node is bellows 4. It also shows that the residual energy of node is more balanced and higher than that without optimitization. Moreover, the more data generated rate, the more effect on energy of nodes.

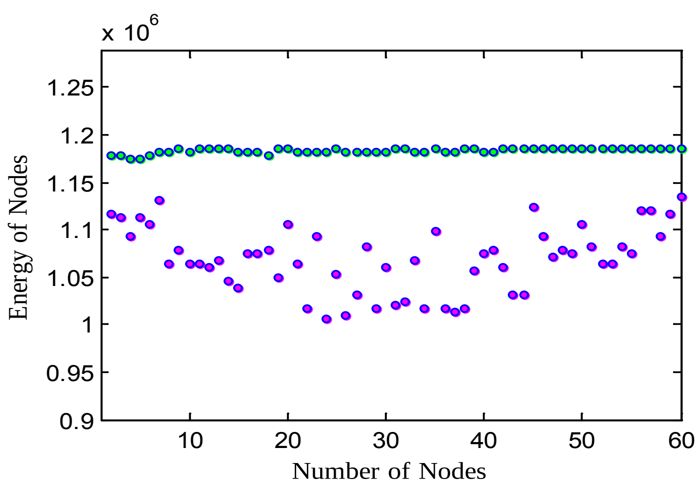


Figure 15. The residual energy(g_v=400bit/s)

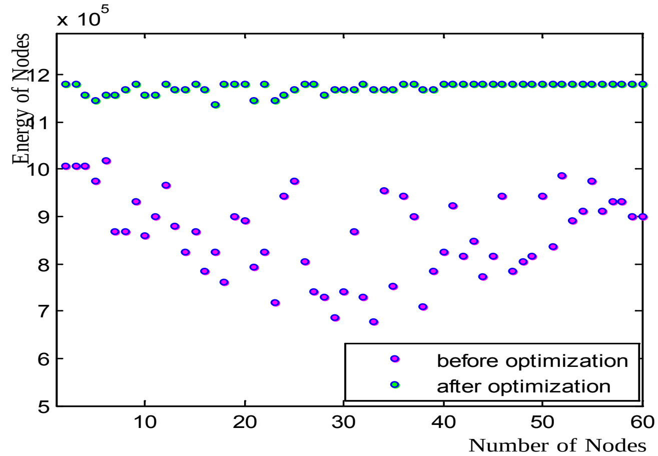


Figure 16. The residual energy (g_v=1200bit/s)

(4) End-to-End Delay

This paper defines end-to-end delay as the average time of which from packet generation to reception by destination node.

End-to-end delay= the point of accomplishing sending data packet/the point of accomplishing receiving data packet.

Figure 17 shows end-to-end delay of four algorithms. With the simulation time changing from 0 to 300s, the end-to-end delay of four algorithms is reduced gradually and tending towards stability. Wherein, EL-BatCA algorithm is more than that of DRNG algorithm and LMST algorithm, however, less than COMPOW algorithm. This is because EL-BatCA algorithm considers energy consumption of a link in the process of communication (related with the distance between nodes) and node residual energy. So the end-to-end delay of EL-BatCA algorithm is caused by the shortest path from source node to destination node.

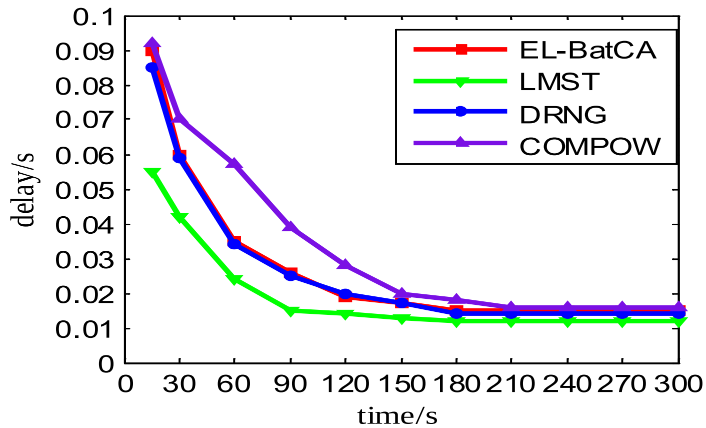


Figure 17. The end-to-end delay

VI. CONCLUSION AND FUTURE WORK

he target of LMST algorithm and DRNG algorithm is local minimum energy depletion, but neglecting the problem of energy balance; the target of COMPOW algorithm is local minimum link load, but neglecting the problem of network load balance. They equally lead to short network span life time. So aiming at the issue of network bottleneck and nodes energy consumption, this paper proposes a topology optimization algorithm (EL-BatCA) based on balanced network energy and load. This paper solves three problems: (1) avoiding network bottleneck, improving network throughout; (2) greatly slowing the rate of nodes dying from main network, extending the network span life time; (3) eliminating the unbalance of network load, reducing nodes energy consumption. Still, this optimization method is also applicable to 3D UASNs However, it has some limitations, such as the transmission power of nodes is always changing; the energy consumption of nodes is not only related with the energy consumed in reception and transmission, but also with the communication distance between nodes. In the future work, more focus will be devoted on the influence of direction of nodes on topology structure.

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