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Optimization of Multiple Gateway Deployment for Underwater Acoustic Sensor Networks

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Abstract. This research aims to develop novel technologies to efficiently integrate wireless communication networks and Underwater Acoustic Sensor Networks (UASNs). Surface gateway deployment is one of the key techniques for connecting two networks with different channels. In this work, we propose an optimization method based on the genetic algorithm for surface gateway deployment, design a novel transmission mechanism—simultaneous transmission, and realize two efficient routing algorithms that achieve minimal delay and payload balance among sensor nodes. We further develop an analytic model to study the delay, energy consumption and packet loss ratio of the network. Our simulation results verify the effectiveness of the model, and demonstrate that the technique of multiple gateway deployment and the mechanism of simultaneous transmission can effectively reduce network delay, energy consumption and packet loss rate.

Keywords: Underwater acoustic sensor networks, gateway deployment, transport mechanism.

1. Introduction

In recent years, UASNs (Underwater Acoustic Sensor Networks) have drawn broad attentions in scientific research, social services, and military applications. UASNs can be widely applied in underwater target tracking and environment monitoring, etc [1][2][3]. Compared with remote sensing methods, UASNs can provide real time in-situ information for shallow-sea and deep-sea monitoring. However, unlike terrestrial wireless sensor networks, UASNs could not use electromagnetic wave as communication media due to its quick absorption in water. Therefore, acoustic signal is often used as a transport carrier in UASNs [4]. Underwater acoustic channel is a complex random channel with variable time-space–frequency parameters, low carrier frequency, long transmission delay, narrowband, strong noise and multipath interference, and many other transmission attenuation factors. Therefore it becomes a highly challenging wireless communication channel. The propagation speed of underwater acoustic signal (approximately 1500m/s, with variation due to minor changes of pressure, temperature, and salinity of water) is lower than electromagnetic wave propagation speed by five orders of magnitude; such high propagation delay will not only limit the interactive application, but also prolong the response time of communication.

Compared to its single gateway counterpart, data in a underwater sensor network with multiple gateways (Fig. 1) do not have to be transmitted via a long path to a fixed surface gateway, but via a path selected in light of optimized network performance (such as minimal delay, minimal energy consumption and least packet loss rate) to one of the available gateways [5]. Depends on the service requirement, the surface gateways can adopt various wireless communication channels such as Cellular network, Zigbee and so on. Note that the data propagation delay from surface gateways to the base station is much shorter than that in underwater acoustic network. The bandwidth of wireless channel can vary from tens of million to hundreds of million bits per second; in a sharp contrast, the data rate of underwater acoustic channel is only between several hundred bits and ten kilobits per second. Moreover, the packet loss rate of surface gateways is much smaller than that of underwater acoustic network. Also compared to radio communication, acoustic communication needs much more energy [6]. The surface gateways can obtain power supply from solar panels or by changing battery periodically. Due to the aforementioned factors, an underwater sensor node can select a path to one of these gateways, aiming to minimize the delay, energy consumption or packet loss rate from it to the gateway. Therefore, how to design an efficient routing algorithm according to different optimization goals, how to select the number and the position of surface gateways are the key research issues of the UASNs with multiple gateways.

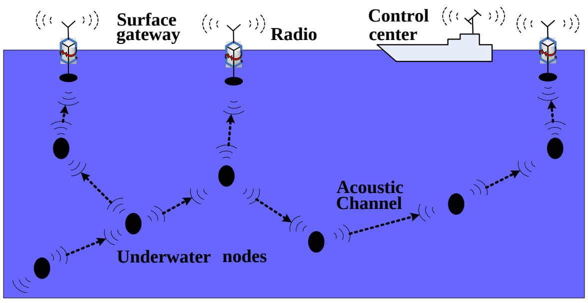


Fig. 1. Structure of Multiple Gateway UASNs

In our previous work [5], we have studied the surface gateway positioning problem based on GA in UASNs and formulated it as an optimization problem. We have shown that using multiple surface gateways can effectively reduce network energy consumptions and delay. However, the routing of data packets from underwater sensor nodes to surface gateways under various objects was not studied.

In this work, we assume that the coordinates of underwater sensor nodes are known. We show how routing is discovered under various objectives such as minimal delay and payload balance, and design a novel transmission mechanism—simultaneous transmission. We further develop an analytic model to study the delay, energy consumption and packet loss ratio of the network. As a result, we verify the effectiveness of the model.

The rest of the paper is organized as follows. Sec. 2 illustrates the related works of multiple gateway deployment. Sec. 3 presents the model for optimization of multiple gateway deployment. Sec. 4 proposes a new mechanism of simultaneous transmissions. Sec.5 describes the process of route discovery. Sec.6 describes gateway deployment based on GA. Sec. 7 discusses simulation results. Finally, Sec. 8 concludes the paper.

2. Related Works

Deployment of multiple gateway in wireless networks can be divided into two categories: one is terrestrial wireless networks, and the other is multiple surface gateway deployment in UASNs.

Most multiple gateway deployment research in terrestrial wireless networks is mainly on the gateway site selection in wireless mesh networks (WMNs). Literature [7] proposed a new routing algorithm called two concurrent path routing (2CPR) for wireless mesh networks with multiple gateways. Literature [8] proposed a gateway selection scheme that considers multiple end-to-end QoS parameters. Literature [9] presented a multiple gateway selection algorithm for WMNs called Weighted Clustering Algorithm (WCA), which is an optimization mechanism based on the Quality of Service (QoS), and used a heuristic algorithm to improve the performance of WCA. The core of WCA is determining the number and location of gateways. However, WCA assumes that nodes locations are known, so that some nodes can be selected as gateways for cluster planning. Aforementioned research focuses on the selection of gateway. For the number of gateways has been pre-determined, the algorithm aimed at selecting the gateway with balanced payload in the network, but did not refer to the gateway position and the effect of gateway number. Literature [10] combined graph partition and spanning tree algorithm, but how to get good computational efficiency of this algorithm is one problem.

In the aspect of network structure, terrain wireless network is similar to a 2-dimensional structure, while underwater acoustic network is a typical 3-dimension structure. In the research of multiple gateways deployment, more emphases have been put on the selection of gateways in mesh network and cluster heads in Wireless Sensor Networks (WSNs). Their general goal is to get balanced payload and optimized QoS. For to the large delay, low bandwidth and limited energy supply in UASNs, the deployment of surface gateways should be focused on the propagation delay from underwater sensor nodes to gateways, energy consumption of underwater nodes and packet loss rate.

For multiple gateway deployment in UASNs, Literature [11] gave a triangular deployment method of 2-dimensional network, and it was aimed at target area coverage with minimal sensors. Literature [12] studied the coverage and routing in 3-dimensional networks. Neither of the two studies involved network structure with multiple sinks nodes (or gateways). Literature [13] used multiple sink nodes to improve the performance of UASNs, but they did not analyze the influence of network delay and energy consumption with multiple gateways. Literature [14] proposed the architecture of surface gateway that has several wireless communication channels and communication protocols. However, they didn't study the effect of the gateway number and positioning. Literature [6][15] focused on how many gateways should be used, and then derived the positions of multiple gateway from the fixed grid on the surface. The queuing delay due to MAC protocol is not considered, the deployment of surface gateways is not resolved with heavy network payload, and the preliminary simulation results were obtained only for one layer (which is 100 meters below the surface). For most of the applications, underwater sensor network would be a 3-dimensional network, because of limited available bandwidth and low signal propagation speed of underwater acoustic channel, data packet collisions, avoidance and reservation in MAC layer protocol will inevitably bring about queuing delay. At the same time, different transport mechanisms will also affect data transmission delay and energy consumption in network, these problems should be considered for 3-dimension UASNs.

To solve the above issues, this paper proposes a new method of surface gateway deployment. Its main idea is to take the fixed underwater nodes as source nodes and the movable surface gateways as destination nodes. We design a novel transmission mechanism—simultaneous transmissions by nodes which are separated by three hops and realize two efficient routing algorithms that achieve minimal delay and payload balance among sensor nodes.

With the delay, energy consumption and packet loss ratio of network as the optimization objectives, we can obtain the optimal positions of surface gateways and a routing that can optimize network performances.

3. Optimization Model

Surface gateway deployment can be treated as an optimization problem. In this section, we discuss the definitions, constraints and objective functions for gateway deployment optimization model.

3.1. Definitions

3.1.1 Nodes

Here let V denote all the underwater sensor nodes, G be all the surface gateways, V' denote all nodes, that is to say $V'=V\cup G$. $I(v)$ denotes all nodes in the communication range of node v, i.e., $I(v)=\{w:w\in V', v\neq w, d(v,w)\leq R\}$, where $d(v,w)$ is the distance between v and w, and R is the communication range of sensor nodes.

3.1.2 Edges

Let E be all the edges $e=(v,w)$, $v\in V, w\in I(v)$, and $e(v,u)=\{e(v,u):(v,u)\ v\in E, u\in I(v)\}$ denote the direction from node v to node u. For any surface gateway node, because the data relaying rate of surface gateways is much higher than underwater nodes, so it doesn't need to consider the relay delay in UASNs. Therefore we can mainly focus on the receiving data for gateways.

3.1.3 Gateway Position

$G(X,Y)$ denotes all surface gateway positions; G_i (x_i, y_i) is the position of the ith gateway.

3.1.4 Queuing Delay of MAC

T_{mac} is the delay caused by MAC layer, which is associated with the connectivity degree of a node. For simplicity, let t_m be the queuing delay of one unit. The queuing delay with only one neighbor is set to $T_{\mathrm{mac}}=0$, then the queuing delay caused by two one-hop neighbors is $T_{\mathrm{mac}}= t_m$, three neighbor links lead to the queuing delay $T_{\mathrm{mac}}= 2t_m$; and so on. For a node with n neighbors, its queuing delay is approximated as $(n\text{-}1)\ t_m$.

3.2. Constraints

In current UASNs, half-duplex communication mode is often adopted. Therefore we set a simple conflict model: when a node is receiving data, it could not send data simultaneously.

3.3. Optimization Variables

We set two optimization variables: the number of surface gateways N and the position of surface gateways G (X, Y). Because gateways are located on the surface, the Z-axis coordinate is similar to a fixed value, so the position variables are simplified as X-axis coordinate and Y-axis coordinate. Our goal is to optimize N and G_i (x_i, y_i) according to the objective functions introduced below.

3.4. Optimization Function

3.4.1 Minimum Delay

The goal is to minimize the total delay of all packets that reach the surface gateway. Packet delay is the sum of all delays generated from every hop along the path from the transmitter to the receiving gateway. Combining queuing delays of the relay-nodes (resulted from the MAC layer or routing layer), delay of each hop composites of transmission delay, queuing delay and propagation delay, the delay t of data on edge e can be written as

$$t(e) = t_{mac}(e) + t_s(e) + t_p(e) = n \times t_m + \frac{L_e}{C} + \frac{d(e)}{v_p} \qquad (1)$$

Here, $t_{mac}(e)$ represents queuing delay, $t_s(e)$ represents transmission delay and $t_p(e)$ denotes propagation delay, n is the connectivity degree of a receiving node (i.e., the number of neighbor nodes in the spanning tree), t_m is the connectivity degree associated with unit queuing delays, L_e is a total length of transmitted data packet in unit of *bit*, including all data generated by the sending node and data to be relayed by the next hop, C is the channel capacity in unit of *bit*/*sec*, $d(e)$ is the edge length, v_p is the underwater acoustic propagation speed.

Therefore, the objective function of minimum total delay is

$$Minimize\left(\sum_{e \in E_r} t(e)\right) \qquad (2)$$

Where E_r stands for all edges of the route spanning tree from the underwater nodes to gateway. Obviously, $e \in E_r$.

3.4.2 Minimum Energy Consumption

The goal is to achieve the minimum energy consumption when all the packets have been transmitted to the surface gateway. If a node sends data L_v, the energy it consumes can be written as

$$\varepsilon(v) = P_S(v)t_S + P_r(v)t_r = \left(P_S(v) + P_r(v)\right)\frac{L_V}{C} \qquad (3)$$

Here, $P_s(v)$ is the transmitting power of node v, $P_r(v)$ is the receiving power of node v. t_s and t_r denote transmission time and reception time respectively. C is the channel capacity in unit of *bit*/*sec*.

Corresponding objective function as:

$$Minimize\left(\sum_{v \in V} \varepsilon(v)\right) \tag{4}$$

3.4.3 Minimum Packets Loss Rate

Packet loss may be resulted from the physical layer, MAC layer, network congestion and other factors. For example, when the data generation period of a node is less than the minimum period required for network transmission, the data must be stored in the memory of a relay-node, and when the memory is full, the data will overflow possibly leading to packet loss. Here considering packet loss generated when traffic constraint is not satisfied, the optimization objective is to minimize packet loss rate of all packets reaching the surface gateway. The packet loss rate of each node can be expressed as:

$$\beta(v) = \frac{f_v - C}{C} \tag{5}$$

Here f_v represents the flow of the node. When $f_v > C$, it indicates that there is packet loss; when $f_v \leq C$, the above formula is zero or negative, and thus there is no packet loss.

The packet loss rate of the whole network is

$$\beta = \frac{\sum_{v \in V} (L_V - C)}{m \times C} \ , \tag{6}$$

where m is the total number of underwater nodes.

The corresponding objective function is:

$$Minimiz\,(\beta) \tag{7}$$

4. Data Transmission Mechanism

The state-of-the-art UASNs protocols fall in to two categories: one is based on the mechanism of competition, and the other is based on the mechanism of time sequence [16]. In order to reduce the delay and energy consumption caused by packet collision and retransmission, we adopt the TDMA scheme of MAC protocol in this research. As the positions of underwater sensor nodes are known, the positions of surface gateways and the route from underwater nodes to gateways can be obtained according to the optimization objective functions (i.e., minimal delay, minimal energy consumption or least packet loss rate). We make use of the initialization method in literature [17], allocate time slots to nodes, and at the same time, send the information of synchronization and routing to underwater nodes by surface gateways. Then the data of underwater nodes will be transmitted according to the routes and time slots periodically.

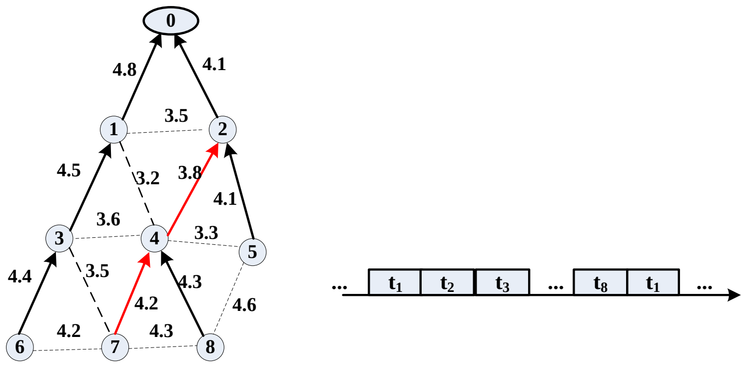
Usually the data transmission from underwater sensor nodes to surface gateways is a directional data flow (from the last hop in the bottom to previous hop until the surface gateway is reached), and the transmission can be based on the Shortest path transport mechanism, Accumulated transmission hop by hop, or Mechanism of simultaneous transmission every three hops.

4.1. Shortest Path Transport Mechanism

With the shortest path transport mechanism, data generated by each node will be transferred to the surface gateway nodes via the shortest path.

As shown in Figure 2(a), each node chooses the shortest gateway from it as the destination, uses the shortest path to reach the gateway. The total delay is the sum of delays of all data packets reaching gateway. The dotted lines indicate the connections, and the solid lines represent the actual transmission paths (numbers beside lines denote delay). Figure 2(b) represents the time sequence. By this method, the time slot of every node could be selected arbitrarily.

When UASNs is small, low delay could be achieved with the shortest path transport mechanism, because the primary delay here is the transmission delay.



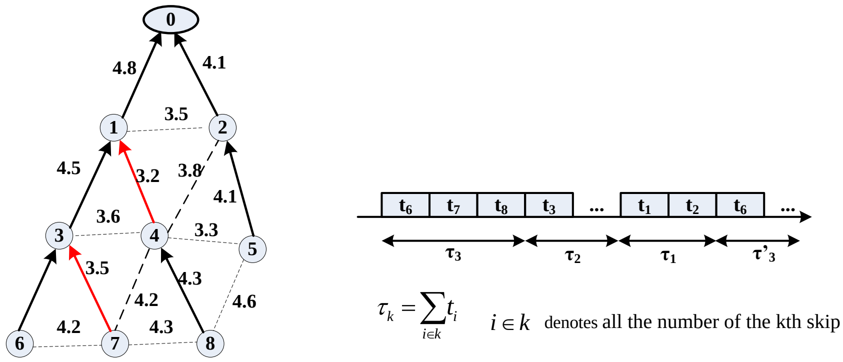
(a) (b)

Fig. 2. Shortest Path Transport Mechanism

4.2. Accumulated Transmission Hop-by-Hop

This transport mechanism is based on the following idea. From the node of the last hop along all other nodes in the path, data is accumulated and relayed hop by hop, and finally arrives at the gateway. This transport mechanism can reduce repeated path propagation delay by nodes of previous hops. The last hop node initiates data transmitting, and accumulates the data ahead hop by hop. The total delay constitutes of transmission delay and propagation delay on the edge with minimum distance as routing edge. In comparison with Figure 2(a), it is obvious that the resulting routing paths are different, as node 4 and node 7 in the Figure 3(a) (numbers beside lines denotes delay). Nodes 7 and 4 select nodes 1 and 3 as the next hop node, respectively, which have smaller delay among the previous hop nodes. Figure 3(b) is the corresponding time sequence. Compared with Figure 2(b), its time sequence must firstly be τ_3, τ_2 and τ_1. Nodes with the same hop number can arbitrarily select their time slots.

Compared with the shortest path transmission mechanism, this approach yields a smaller total delay when there are more hops, because it reduces repeated transmission delay.



(a) (b)

Fig. 3. Accumulated Transmission Hop-by-hop

4.3. Simultaneous Transmission every Three Hops

When two nodes are separated by three hops (such as nodes 15 and 4 shown in Figure 4(b)), there will be no conflict in the channel utilization. So one improved method of Accumulated Transmission is simultaneous transmitting by every three hops. First of all, the last hop nodes (e.g., nodes 15 and 16) transmit data ahead, and at the same time, nodes three hops away from them (i.e., nodes 4, 5, and 6) also send data ahead. When these nodes have completed their transmissions, nodes of the second last hop and corresponding nodes three hops away from them begin to send data. Similarly, the process repeats until all data have reached the gateways. As a result of the simultaneous transmission, the transmission delay could be decreased remarkably for the data that reach the gateway.

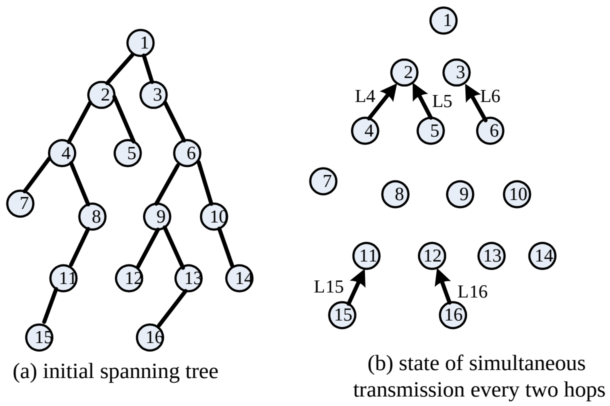


Fig. 4. Simultaneous Transmissions every Three Hops

Figure 5 is the corresponding time sequence of data transmission. Similar to figure 3(b), the last hop and its previous three hops firstly send data simultaneously, take the largest delay in the group of nodes as the transmission delay of this group, then the second last hop and its previous three hops send data simultaneously to gateway, and a period of data collection is completed. Figure 5 also shows, when nodes of the third last hop (τ'_5 in the figure) send data in the first period, node of the last hop can send data in the second period (τ_5 in the figure). Obviously, this transmission scheme can efficiently reduce the delay of the whole network.

With simultaneous transmission every three hops, the minimum delay in the corresponding optimization model must use formulas 8 and 9 instead of formulas 1 and 2; the delay consumed in the transmission of every hop is:

$$t(i) = \max\left(n_i \times t_m + \frac{L_i}{C} + \frac{d_i(e)}{v_p}, n_{i-3} \times t_m + \frac{L_{i-3}}{C} + \frac{d_{i-3}(e)}{v_p}, \ldots, n_{i-3k} \times t_m + \frac{L_{i-3k}}{C} + \frac{d_{i-3k}(e)}{v_p} \right)$$
$$i = N, N-2, \ldots 1; i-3k > 0; k = 1, 2, \ldots \tag{8}$$

where $n_i \times t_m$ is the waiting delay of all nodes of the ith hops, L_i/B is all the transmission delay of the ith hop, d_i/v_p is all propagation delay of the *i*th hop, N is the maximum number of hops.

The total delay of all the packets can be expressed as:

$$Minimize[t(e)] = \left(\sum_{i=1}^{N} t(i) \right). \tag{9}$$

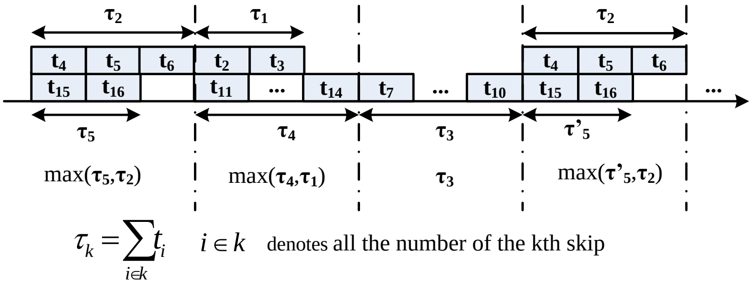


Fig. 5. Time sequence of Data transmission

5. Route Discovery

The underwater nodes, surface gateways and the links between them can be abstracted as a connected graph. To obtain the available routes, the underwater nodes can be viewed as source nodes and surface nodes can be viewed as destination nodes. So the network routes Forms the structure of the minimum spanning trees derived from different objective functions.

5.1. Minimum Delay Spanning Tree

The main contributor of delay are total transmission delay and total propagation delay. The former is related to network size (in terms of hops). The smaller the network, the less transmission delay is in relaying data. Therefore, in order to obtain the minimum total transmission delay, we adopt minimum hops as the optimization goal when constructing the minimum spanning tree. Because total propagation delay is related to total path length, in order to obtain the minimum total propagation delay, we consider the shortest path as the best goal on the spanning tree. Combining the two objectives, we firstly use the minimum hop number and shortest path spanning tree, as shown in left part of Figure 6, treat the gateways as the vertex set and all the underwater sensor nodes form the endpoint set. Then find the edges between the vertex set and endpoint set as the spanning tree. If one endpoint in the endpoint set simultaneously connects many vertexes, then the shortest edge is retained and other edges are removed. Adding all connected endpoints to vertex set, while remove all connected endpoints from the endpoint set, check whether the endpoint set is empty, if not empty, it denotes there are still underwater nodes not included in the spanning tree, so repeat the above steps until the endpoint set is empty.

There is an exceptional case we must consider as shown in Figure 7. Assuming nodes 2 and 3 generate data of length L, acoustic speed is v_p, the distance between nodes is d, channel capacity is C, so the time when data arrives at relay-node 1 before adjusting the spanning tree is $T = 2t_m+(d_{2,1}+d_{3,1})/v_p+2L/C$, and after adjusting the spanning tree, the time $T'=2t_m+(d_{2,1}+d_{3,2})/v_p+3L/C$, so the delay is changed by $\Delta T=L/C-(d_{3,1}-d_{3,2})/v_p$. When ΔT is negative, it denotes the delay is decreased, so the adjustment is effective.

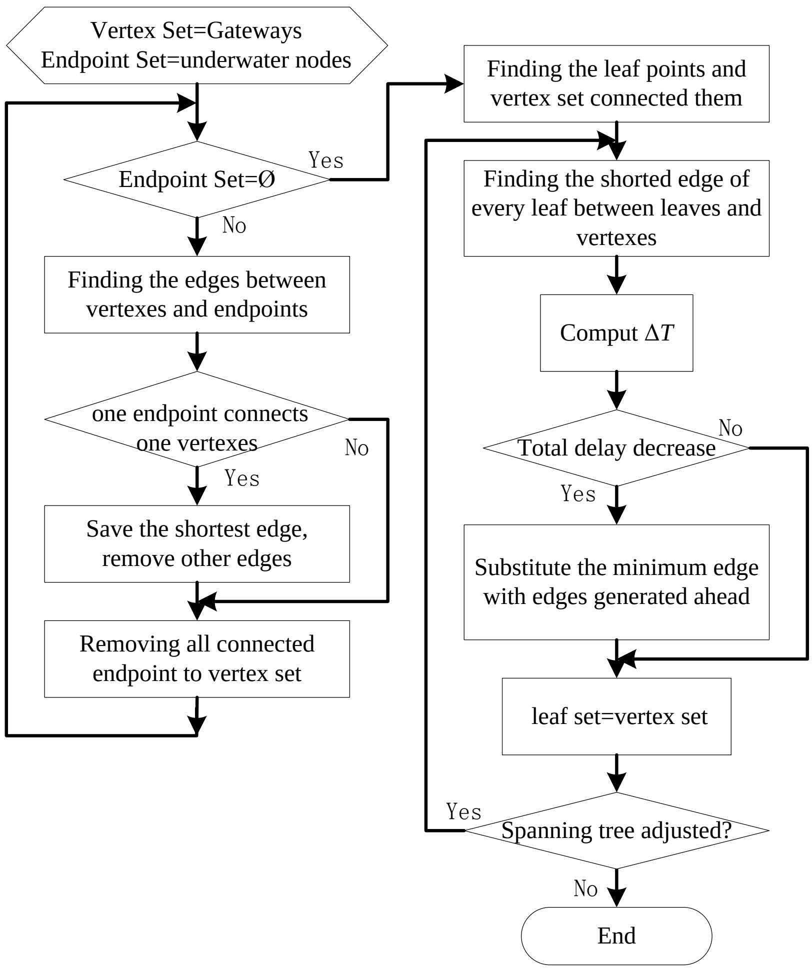
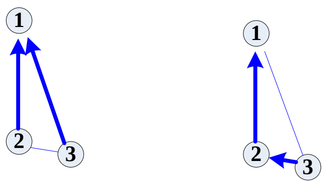


Fig. 6. Flow Chart of Constructing Minimal Delay Spanning Tree

The flow diagram is shown in the right part of Figure 6. First, the algorithm finds all the leaf nodes and the smallest edges connected with them in the spanning tree which is obtained by minimum number of hops and smallest path, and substitute the minimum edge for connected edges with leaf node in the spanning tree. Judge whether delay is decreased, if so, replace the old edges with new ones in the spanning tree, continue this process until all leaf nodes have been determined, and then remove the leaf nodes and edges connected with them in the spanning tree, find the new leaf in the residual tree. As the judgment mentioned above, the decreased propagation delay and increased transmission delay are (transmission delay is (n +1) * L / C, in which n is the number of nodes whose data should be relayed via this leaf node in the initial spanning tree connected) determined until there is no need for adjustment of spanning tree, at this time, the spanning tree with minimum total delay is obtained. Figure 8 and figure 9 are the minimum delay trees derived by 2-dimensional simulation, and figure 8 is Spanning tree before adjustment while figure 9 is that after adjustment.



$$T=t_{mac}(2)+t_s(2)+t_p(2)+t_{mac}(3)+t_s(3)+t_p(3)$$
$$=t_m+d_{2,1}/v_p+L/C+t_m+d_{3,1}/v_p+L/C$$

$$T'=t_{mac}(2)+t_s(2)+t_p(2)+t_{mac}(3)+t_s(3)+t_p(3)$$
$$=t_m+d_{2,1}/v_p+2L/C+t_m+d_{3,2}/v_p+L/C$$

$$\mathbf{\Delta T=T'-T=L/C-(d_{3,1}-d_{3,2})/v_p}$$

Fig. 7. The Adjustfment of Total Delay.

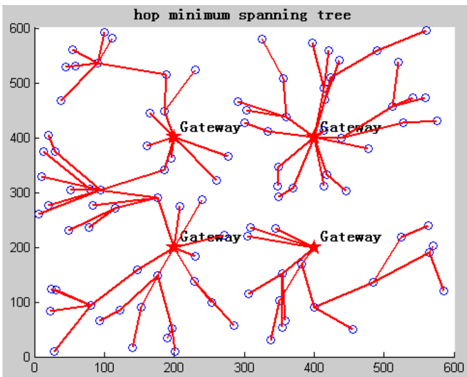


Fig. 8. Minimum Hop-number Spanning Tree of 2-dimensional Diagram

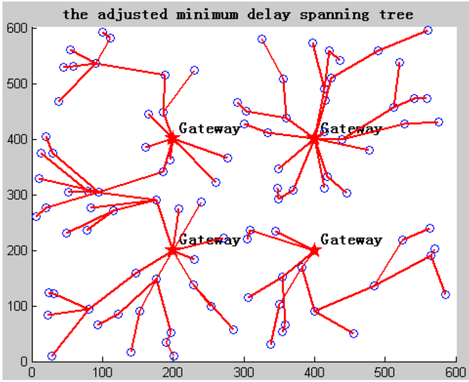


Fig. 9. The Adjusted Minimum Delay Spanning Tree of 2-dimensional Diagram

5.2. Minimum Spanning Tree with Balanced Energy

In UASNs, the energy consumption is one of the key issues we concern about, but how to balance all network nodes, and make the network connectivity as long as possible is one of the research emphasis in UASNs area. The energy consumption of a node is related to the data transmission and reception of the nodes. Therefore in order to achieve balanced energy in the network, we can solve the problem in a perspective of the balance between transmitting data and receiving data. The amount of data being sent and received by a node is inversely proportional to the node connectivity degree; energy balance can be realized when network connectivity degree of node is the smallest, and total energy consumption can be minimized when the hop number of every node is the smallest. Therefore, to achieve energy balanced minimum spanning tree, we can first create spanning tree by the minimum hop number.

Figure 10 is the flow chart. Similar to the left part of Figure 6, we create the connectivity graph via the minimum hop number. When the endpoints of the same hop number is connected with multiple vertices, select the edges connected to the least degree vertices, and remove the edges connected to other vertices. The right part of the figure 10 shows the adjustment when the payload is not balanced as nodes 1 and 8 in Figure 11. As it implies, firstly find the relay-node set of spanning tree, then find the relay-node with the heaviest payload and the corresponding endpoints set, and finally calculate the edges between all nodes in the endpoint set and all other nodes other than the endpoints, find the shortest edge. Then put the node into the endpoints set connecting neighbor relay-nodes of this node with the shortest edge. Compute the adjusted maximum payload. If the maximum payload is decreased, then remove the initial edges in the spanning tree; make the new edge join the spanning tree, at the same time, update maximum payload. Next, judge whether the extreme point set is empty. If it is, it indicates that the adjustment of this node is completed, and then removes it from the relay-node set. Judge whether the relay-node set is empty, if it is, it denotes that the adjustment of all nodes has completed. Figure 12 is a 2-dimensional minimum spanning tree with balanced energy.

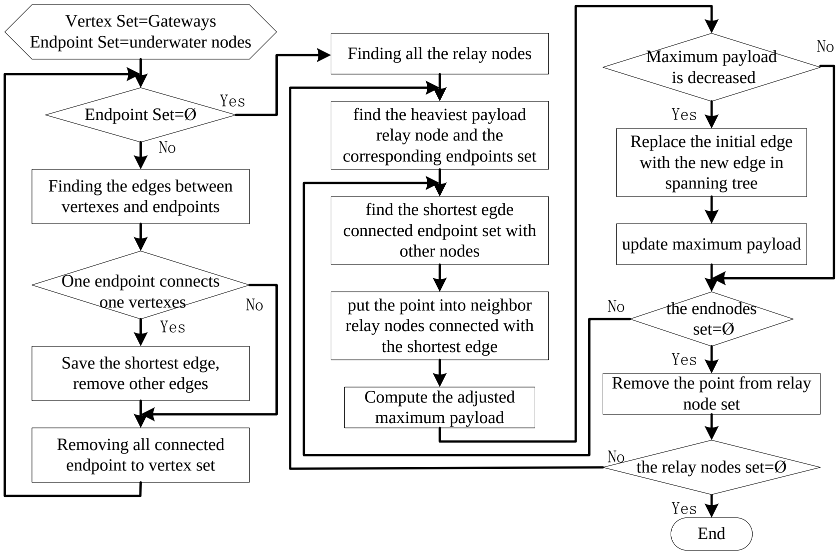


Fig. 10. Flow Chart of Minimum Spanning Tree Obtained with the Objective of Balanced Energy

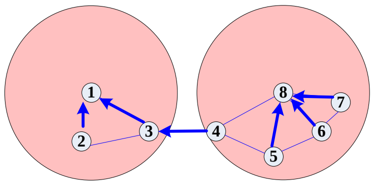


Fig. 11. Adjustment of Payload Imbalance

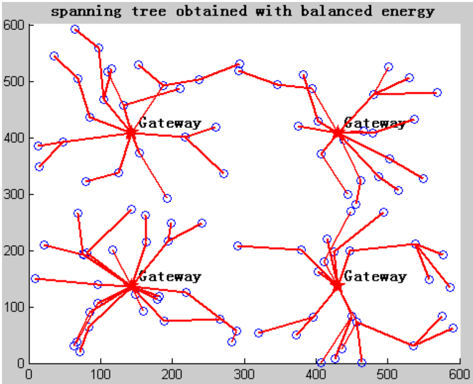


Fig. 12. 2-dimensional Spanning Tree Obtained with the Objective of Balanced Energy

6. Gateway Deployment Based on GA

Genetic algorithm is a global optimized probability searching algorithm, which simulates the evolution process of creature in nature. The population consists of multiple individuals, and it is the computation object, by a repeating iterative process, the individuals will be continuously put on genetic and evaluative operation, and individuals with higher fitness will be transferred to the next generation via the principle of survival of the fittest. So the ultimate result is that individuals with the highest fitness. Because it is a heuristic search based on population, it will find multiple solutions satisfying different preferences in one optimization if it is used in the problem of multiple objectives optimization, and it can handle the objective functions and constraints of all types. Here, we adopt the genetic algorithm, where genetic individual is set to be x coordinate and y coordinate of surface gateways, and the search scale is set to the surface area that underwater nodes corresponds to.

The realization process is as follows: first, when the numbers and location of gateways are fixed, a best route is obtained from underwater nodes to gateway depending on different object functions. When the number of gateways is fixed, different locations of gateways lead to different best routes, so the problem of deployment can be turned into finding the best location of the gateways that achieves the optimal objective function. Mathematical analysis could be used to solve partial differential equations. As the number of gateways increases, it will be very complex to solve this question, so a heuristic search algorithm can be used to obtain the optimal or near-optimal solution. By changing the number of gateways, we can get the corresponding gateway number and a best network performance chart, and get the critical parameters (the minimal gateway number making network performance optimal).

7. Simulation and Analysis

7.1. Simulation Setup

In order to evaluate the performance of multiple gateway optimal deployment, we simulate a UASN as shown in Figure 13. The packet length is set as L= 400 *bits*. The underwater sound propagation velocity is v_p = 1500*m*/*s*, transmission power $P_s(v)$= 1 *watt*, and reception power $P_s(v)$= 0.2 *watt*. Note that although data packet collision, avoidance, reservation, and waiting cause power consumption in the MAC layer, such power is generally far less than the transmission power. Also the network is randomly deployed in an area of 600*m* × 600*m* × 600*m*, where the largest sound communication distance of underwater sensor nodes and gateway nodes is R = 150*m*. All underwater sensor nodes are arranged randomly and network connectivity can be maintained. The surface gateway location selection uses GA, running parameters are: the sample size is 40, individual length is 25, number of generations is 25, crossing probability is 0.7, and mutation probability is 0.028. The minimum value of each objective function is regarded as a target. The MAC layer adopts TDMA.

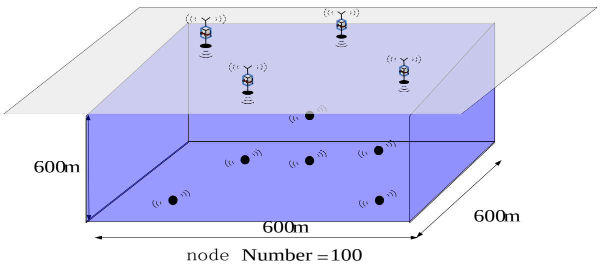


Fig. 13. The Configured Scene for Our Simulations

7.2. Result Analysis

We use a corresponding critical parameter that the minimum number of gateways can get optimum network performance, in order to demonstrate the optimization deployment and verify the advantages of multiple surface gateways in real network deployment.

7.2.1 Relation between the gateway number and network performance

Under usual circumstances, when the number of surface gateways increases, network performance will be improved. To verify this, we derive optimal location deployment of 1-25 gateways using GA according to different optimization objectives. Figures 14 and 15 compare the results of delay and energy consumption calculated by GA after three simulation runs with that calculated randomly. Accumulated transmission hop-by-hop is employed in our simulation. The channel capacity C = 9600. The vertical axes of the figures represents packet delay and energy consumption required to reach the gateway, respectively, while horizontal axis shows the number of gateways. From the coincidence degree of the three curves in the graph, we can see stable computational results can be obtained by GA. The simulation results show that the increase of surface gateways can dramatically improve the network performance, in comparison with a single gateway,. It also indicates that the improvement degree of network performance by increasing surface gateways is not evident as surface gateways increases in some cases. When the number of surface gateways reaches a threshold, further increasing the number of gateways cannot noticeably improve network performance. This is because when gateways are enough, underwater nodes can communicate with the nearest gateway in its communication range instead of choosing other gateways newly added to the network. Therefore, it is redundant to increase the surface gateways.

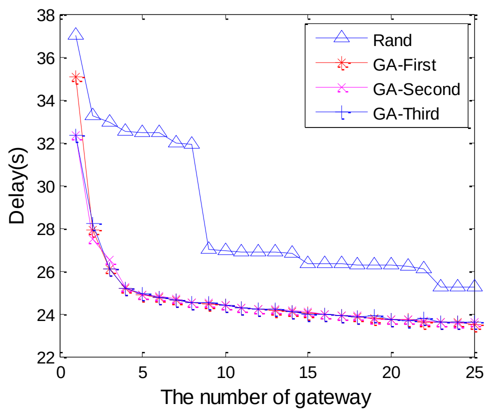


Fig. 14. Delay and the Number of Gateways

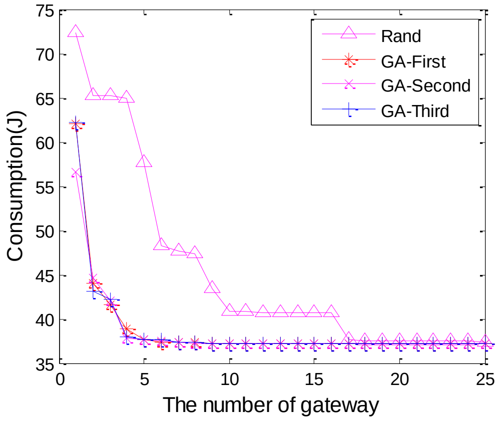


Fig. 15. Energy and the Numbers of Gateways

7.2.2 Effect of Channel Capacity

Obviously, when the ratio of total data generation rate to channel bandwidth of node increases, (including the transmission of its generated data and data to be relayed), more nodes are needed to handle the increased traffic in order to make it accommodate the increase of data transmission rate. We can increase the minimum amount of surface gateways to solve the problem. On the other hand, the increase of channel capacity will reduce the network payload and make it easier to satisfy the constraint of balanced flow.

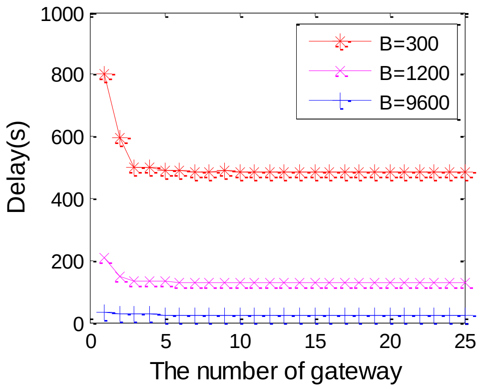


Fig. 16. Delay and the Number of Gateways under Different Rates

To test the effect of channel capacity on network performance, we compare different channel capacities (300,1200 and 9600 bps), and the simulation results show that as network payload increases, the degree of performance improvement decreases while increasing the number of surface gateways, as the network gradually reaches a saturated state. Figures 16 and 17 show the impact of channel capacity on network delay and energy consumption, respectively. Figure 18 shows the effect of different data rates on the packet loss rate of network.

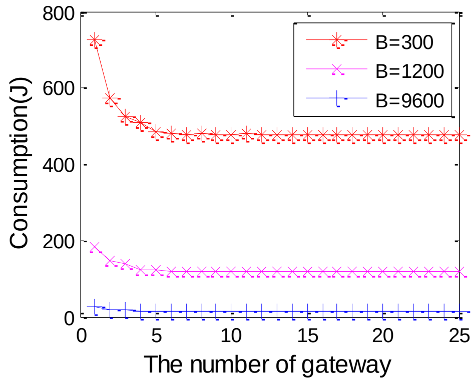


Fig. 17. Energy and the Number of Gateways under Different Rates

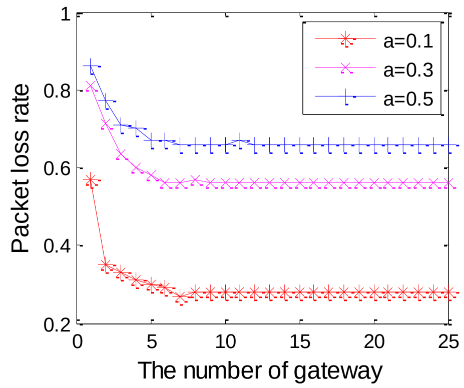


Fig. 18. Packet Loss Rate and the Number of Gateways under Different Data Generation Rates (g_v=α×β is the number of different generation rate)

7.2.3 The Impact of Different Transmission Mechanisms

When the network structure is more complex (e.g., with more hops or heavy payload), different transport mechanisms will result in different network performances, and the mechanism of simultaneous transmission every three hops has a distinct advantage. As shown in Figure 19, when C = 1200, this mechanism is compared with accumulated transmission hop-by-hop, where the delay is reduced almost by half. This proves that a lot of nodes simultaneously send data and total delay is reduced. Because simultaneous transmission every three hops can reduce the propagation delay, but energy consumption of nodes is only related to transmission delay, the mechanism of simultaneous transmission every three hops can make little improvement on energy consumption.

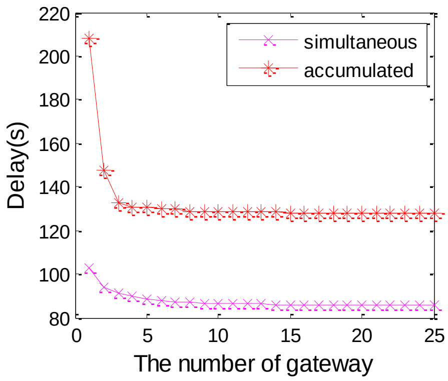


Fig. 19. Delay and the Number of Gateways under Different Transport Mechanisms

8. Conclusions and Future Work

In this paper, the deployment of surface gateways in UASNs is studied, by considering the acoustic characteristics. More specifically, we propose an optimization method of surface gateways deployment dynamically based on genetic algorithm, design a novel transmission mechanism—simultaneous transmission, and realize two efficient routing algorithms that achieve minimal delay and payload balance among sensor nodes. The simulation results show that the use of multiple surface gateways can effectively improve network performance; the number of surface gateways depends on channel capacity (network capacity) and the deployment of underwater sensor nodes; surface gateway location derived by the GA has good stability; and the network delay can be greatly reduced by this mechanism.

In the future, we will investigate possible improvements on joint deployment of surface gateways and underwater nodes. Other future work includes a more accurate conflict model, and selection of suitable MAC protocols that reduce queuing delays.

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