A Cross-Layer Protocol with High Reliability and Low Delay for Underwater Acoustic Sensor Networks

Ning Sun[1], Huizhu Shi[1], Guangjie Han[1](✉), Yongxia Jin[1], and Lei Shu[2]

[1] College of Internet of Things Engineering, Hohai University, Changzhou, China
sunn2001@hotmail.com, graphite_123@126.com, hanguangjie@gmail.com, jinyx@hhu.edu.cn
[2] Guangdong University of Petrochemical Technology, Maoming, China
lei.shu@ieee.org

Abstract. A cross-layer protocol is proposed to deal with the problems of high latency, low bandwidth and high bit-error-rate (BER) in underwater acoustic sensor networks (UASNs). Nodes are organized as clusters based on depth and the nodes with same depth belong to same cluster and cluster head (CH) is chosen by the CH in high-level depth. At network layer, nodes in different depths send packet to their CH hop by hop and CH transmits the aggregated data to the one-depth higher CH till the data arrives at sink node in surface; At MAC layer, a CSMA/CA-based MAC protocol is used in each cluster while CHs use a pre-defined schedule to allocate the channel; At physical layer, nodes change the transmission power and frequency to decrease channel collision and energy consumption in a self-adaptive way. According to the simulation results, it brings benefits in improving transmission reliability and decreasing transmission delay.

Keywords: Underwater acoustic sensor networks · UASN · Cross-layer · Reliability · Low delay

1 Introduction

Underwater wireless sensor networks (UWSNs) [1] refers to the network in which the underwater sensor nodes with low energy consumption and shorter communication distance are deployed to the underwater area and the network are established in a self-organizing way. UWSNs often subject to the following challenges:

The work is supported by “Qing Lan Project”, “the National Natural Science Foundation of China under Grant 61572172”, “the Fundamental Research Funds for the Central Universities, No. 2016B10714”.

J.-H. Lee and S. Pack (Eds.): QShine 2016, LNICST 199, pp. 377–386, 2017.
DOI: 10.1007/978-3-319-60717-7_37

(1) Acoustic communication is generally adopted in UWSNs due to its physical characteristics. However, bandwidth achievable in underwater acoustic signals is strictly limited;
(2) Underwater channel attenuation is serious and the attenuation is variable;
(3) Due to the flow of water currents, drift may cause the sensor node's communication connection not reliable, and high BERs and temporary communication interruptions may occur;
(4) Node battery energy is limited and it is difficult to replaced [2].

Traditional wireless sensor network protocol uses a layered architecture, therefore when designing the network, each layer is designed to be independent of each other. Although the method of layered protocol makes the design simple, but it cannot guarantee the optimal design of the entire network. By using adaptive cross-layer protocol in sensor networks and considering the network protocol stack as a whole, levels that do not adjacent to each other can logically achieve more balanced performance [3].

In this paper, a novel cross-layer protocol is proposed to deal with the problems of high BER and high latency in UASNs. Based on depth in water, the nodes are organized as different clusters. The nodes in same depth organizes a cluster. The first-depth CH is chosen by sink node in water surface and then it designates the second-depth CH and CHs are chosen by this way in turn. At network layer, nodes in different depths send packet to their CH hop by hop and CH transmits the aggregated data to the one-depth higher CH till the data arrives at sink node in surface; At MAC layer, a CSMA/CA-based MAC protocol is conducted in each cluster while CHs use a pre-defined schedule to allocate the channel; At physical layer, nodes change the transmission power and frequency to decrease channel collision and energy consumption in a self-adaptive way. The proposed cross-layer protocol integrating the physical layer, MAC layer and network layer optimizes network performance in terms of reliability and latency.

The paper is organized as followings: In Sect. 2, we discuss several related works. In Sect. 3, we present the proposed cross-layer protocol in details. In Sect. 4, some simulations are conducted and the results are discussed. In the end, we draw the conclusion in Sect. 5.

2 Related Works

In recent years, cross-layer protocols for UASNs continue to be presented [4–7]. [5] proposes an underwater cross-layer protocol, assessing different power and frequency allocation scheme with the minimal energy consumption. The method uses DACAP protocol in MAC layer, and the functions of MAC layer and physical layer are closely coupled. And it uses FBR protocols in routing layer, which determines the routing protocols used in different standards, and then uses different power levels. But it needs to send RTS, CTS packet to exchange information in FBR protocol, that easily lead to excessive delays in underwater wireless sensor networks. At the same time, when the network is sparse, it has to repeatedly expand the size of the arc to find the next hop nodes [6].

[7] proposes a centralized cross-layer scheduling protocol for underwater wireless sensor networks, analyzing the relationship between transmission power and distance and frequency in underwater single link. Cluster heads collect and estimate the delay and distance information of each node by broadcasting beacon form. In the MAC layer, scheduling each link to reduce conflicts, by considering the characteristics of the delay of underwater link; In the physical layer, sensor nodes reduce energy consumption by adaptively changing the transmission frequency and transmission power. However, this method is only applicable to a centralized network, and when the network nodes is more, further consideration of energy-saving strategies is needed.

3 The Cross-Layer Protocol for UASNs

3.1 Network Model

Supposing that sensor nodes are deployed in a small-scale marine area, the marine areas can be represented by a cube model. With base station deployed in the middle of the horizontal plane, nodes underwater are deployed at different levels. In addition, different levels of sensor nodes carry different depth information. And we only analyze three-layer model, which is shown in Fig. 1. The nodes with the same depth of information can be divided into a cluster.

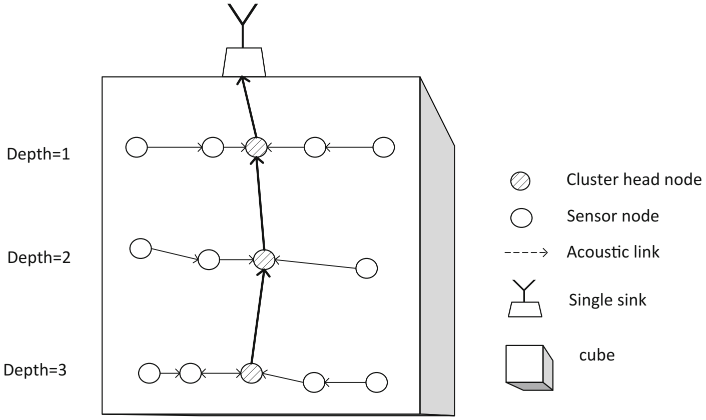

Fig. 1. Network model

3.2 Algorithm for Cluster Head Election

Sink node transmits a beacon message to elect the header of cluster in which the depth equals one (depth = 1). After receiving the beacon, the corresponding sensor nodes send an ACK message to the sink node in a competition period T1, using CSMA mechanism. Sink node records the ACK information received from the first record, and selects the head node of cluster in which the depth equals one (depth = 1). At the end of the competition period T1, the appointment message will be sent to the corresponding cluster head node and the election of cluster head in the first cluster is completed.

(1) The beacon sent by sink node includes message that the value of depth (Depth = 1), the position of the sink node, and the time permitted for ACK.
(2) Normal sensor nodes sends an ACK message to the sink node in a competition period T1, using CSMA mechanism. If some nodes failed to send ACK on time, they will abandon sending ACK. So it can avoid conflict with the appointment message from sink node.
(3) Once receive appointment messages, CH whose depth value equals one will broadcast the message that itself has been the cluster head node, with the maximum level of power. Other normal nodes in the cluster will record the ID and position of CH once they receive the message from the CH. Then, the CH continues to transmit a beacon message to elect the CH in which the depth equals two (depth = 2). And so on, CH of each depth and the propagation route between CHs have been formed.
(4) As is shown in Fig. 2, The formula of the relationship between the propagation loss and the distance in UASNs is:

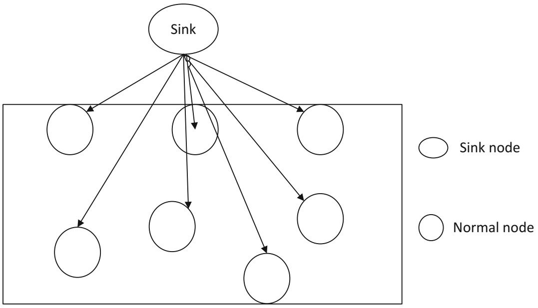

Fig. 2. Beacon transmission

$$TL = n \cdot 10 \lg r + \alpha r \tag{1}$$

It can be calculated that the node in the middle position can receive beacon earlier and then send ACK earlier. Assume that the movement of ocean currents cause the absolute position of the nodes to changes, but the relative position is substantially unchanged. As a result, frequent re-election of cluster node is not a must.

(5) Taking the energy of cluster into consideration, sink node can send reset massage after a long time. Waiting for all nodes have stopped transmission, the next round of initialization will be launched.
(6) Take underwater model of three-layer depth as an example, sink grasps the deep information of sensor networks in advance. Transmission slots of each cluster head are ruled in beacon messages while the route between clusters is formed as soon as the cluster head is elected. When the information collection in the cluster

is ended, CH in the bottom of the slot allocation will send information it has collected to the CH which is in superior depth, uploading the data to another after the data fusion.

3.3 The Cross-Layer Mechanism

3.3.1 Initialization

The goal of initialization is to realize the partition of clusters, the election of cluster head nodes, and the formation of routing path from nodes to sink node.

(1) *Divided clusters*

First, we need to establish the marine cube model. The base station is deployed in the middle of level, and assuming that the movement of ocean currents cause the absolute position of the nodes to changes, but the relative position substantially unchanged.

Sink node transmits a beacon (beacon) message to elect the header of cluster in which the depth equals one (depth = 1). After receiving the beacon, the corresponding sensor nodes sends an ACK message to the sink node in a competition cycle T1, using CSMA mechanism. Sink node records the ACK information received from the first record, and selects the head node of cluster in which the depth equals one (depth = 1). At the end of the competition period T1, the appointment message will be sent to the corresponding cluster head node and the election of cluster head node in the first cluster is completed.

The cluster head node who receives appointment messages will broadcast the message that itself has been the cluster head node, with the maximum level of power. Other normal nodes in the cluster will record the ID and position of the cluster head node once they received the message from the cluster head node. Then, the cluster head node whose depth equals one will transmit a beacon message to elect the header node of cluster in which the depth equals two (depth = 2). And so on, the cluster head node of each depth and the propagation route between cluster head nodes has been formed.

Normal nodes in the cluster who received the broadcast message from the cluster head node can obtain transmission power level Pr based on received signal strength (RSSI) and then can calculate the path loss according the formula:

$$\mathrm{Ploss} = \mathrm{PAP} - \mathrm{sent} - \mathrm{Pr}\,. \tag{2}$$

Also, they can estimate the distance between themselves and cluster head node according to the formula:

$$\mathrm{d} = \mathrm{g}(\mathrm{Ploss}, \mathrm{f}). \tag{3}$$

If the $\mathrm{d} < \mathrm{d}_{\mathrm{onedrop}}$, the node is determined within the range of own-hop of head node in a cluster, and it then transmits ACK message to the cluster head node. A star topology has been formed around the cluster head node and is shown in Fig. 3.

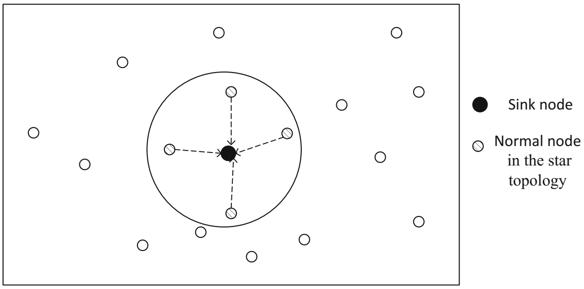

Fig. 3. Star topology

(2) *Distance estimation in the star topology*
Once received the broadcast message from the cluster head node, Normal nodes in the cluster can obtain transmission power level Pr based on received signal strength (RSSI) and then can calculate the path loss according the formula 2.
Also, they can estimate the distance between themselves and cluster head node according to the formula 3.
And preparing for power control, they can estimate both distance and optimal communication threshold $R_{threshold}$ witch can determine the optimum power to neighboring nodes successful communication.

(3) *Delay estimation in the star topology*
According to the agreement of [7], in star topology, sensor nodes in the one hop range of the cluster head node using CSMA mechanism to send ACK information to CH. Once CH receives ACK, it can estimate value of the propagation delay *tp* according to the propagation time difference [8]. The propagation time difference is shown in Fig. 4.

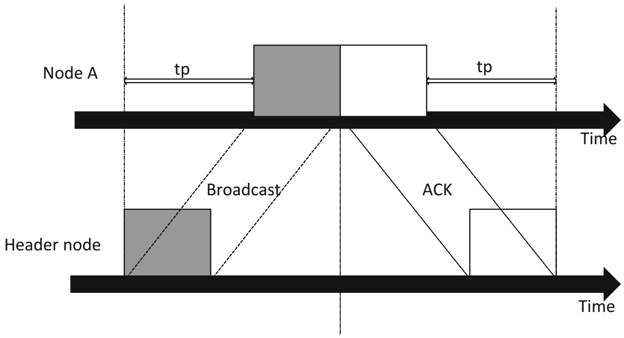

Fig. 4. Delay estimation

3.3.2 Communication Phase

(1) *Collision Avoidance between clusters*
As shown in Figs. 5 and 6, different clusters will be divided into different communication slots in the election when chose the cluster head node. First, sink node transmit time schedule by beacon transmission, and the time schedule will be transmitted to other normal nodes in the cluster and the cluster head node whose depth value is bigger than one by broadcast. In T1 slot, the sensor node whose depth equals one (depth = 1) will send an ACK message to the sink node. The T3 slot is for cluster internal information collection.

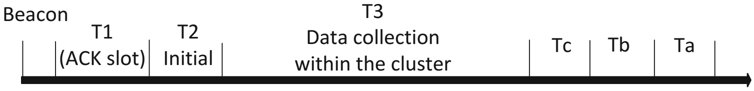

Fig. 5. Room graph slot

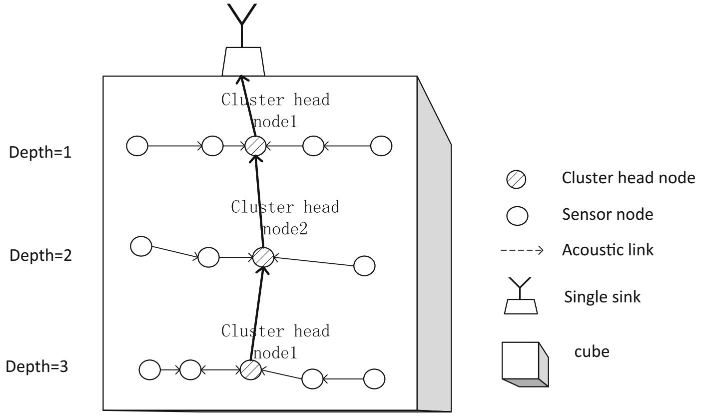

Fig. 6. Routing process

Take the underwater model with three depths for example, in Ta slot, CH3 will send the fusion date to CH2 with maximum level of power. in the slot *Tb*, CH2 fuses date, and then sends the date to CH 1. in *Tc* slot, CH1 will send the fusion date to the sink node with maximum level of power.`

(2) *Collision Avoidance within clusters*
As shown in Fig. 5, in T3 slot, data is transmitted within the cluster. As shown in Fig. 7, the nodes in the hop range of cluster head nodes only receive data and do not transmit data in the period T3-1; the nodes in the hop range of cluster head nodes communicate with the cluster head node in the period T3-2; and in the period Ta/Tb/Tc, other normal nodes in the cluster go to sleep, the cluster head node sends date to the sink node in assigned time period.

As shown in Fig. 8, normal nodes in the cluster send RTS to node A, and nodes around reply CTS that contains location information and residual energy. Then node A chooses node B who has short distance. Therefore, conflict within the cluster can be effectively avoided. Then node A sends data that contains the ID of node B to node B.

Fig. 7. Cluster head timeslot

(3) *Collision Avoidance in a star topology*
According to the agreement of the [7], space-time factors affect the transmission power between the two nodes. And node adjust the power based on spatial factors, adjust the delay according to the time factor (spatial factors include the distance between nodes, time factors including the delays caused by changes in the external environment). Each link can use *fopt(d)* and *Popt(d)* to control of their head to the cluster channel power and frequency, based on the distance and delay estimates obtained in the initialization phase, so that the link can achieve optimal energy consumption, the total energy consumption of the system is minimized.

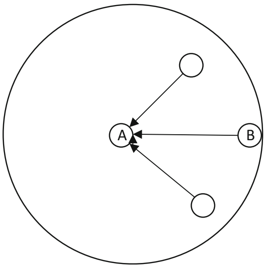

Fig. 8. Normal nodes send CTSs.

In underwater environment, the link propagation delay from point to point is longer, so the delay from each cluster to head node is not the same. Therefore, in order to avoid conflicts, it can make full use of system resources in time. through reasonable scheduling. As is shown in Fig. 9, when the cluster head node broadcasts a scheduling package, the delay of the package arrives at the node A and node A is Ta and Tb. If $2tB > 2tA + TdataA$, although the nodes A and B send signals to the cluster head in the same time, signals will arrive cluster head without conflict. The data transfer time *Tdata* can be calculated according to the transmission data packet length *Ddata*:

$$\mathrm{Tdata} = \mathrm{Ddata}/\mathrm{Rate}. \tag{4}$$

and Rate is the transmission rate.

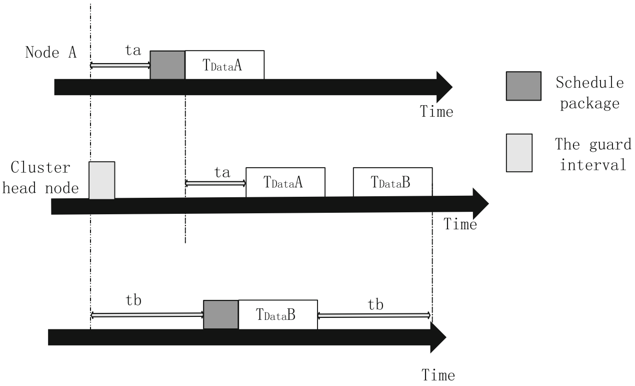

Fig. 9. MAC schedule.

4 Performance Evaluation

In this part, we simulate this protocol in MATLAB to evaluate the performances in terms of transmission reliability and delay. Simulation scenario is similar to the topology shown in Fig. 1. The underwater acoustic sensor network is deployed on the bottom of a shallow water volume of 100*100*600 m^3. Sink node is fixed at the center of a horizontal plane. The generation of data follows the Poisson distribution, and wave frequency is set to 5–25 kHz, the control packet length is set to 30bits, the packet length is set to 1024bits, and the threshold level is set to SNR = 20 dB.

When the depth of the network topology is 1, 2, 3, 4, 5, the success rate of transmission and propagation delays are calculated. Simulation results are shown in Figs. 10 and 11.

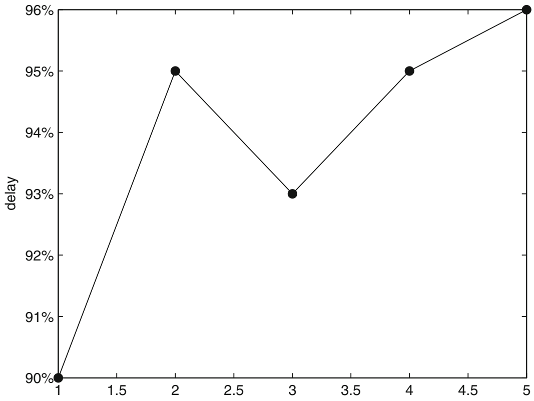

Fig. 10. The relationship between delay and layers

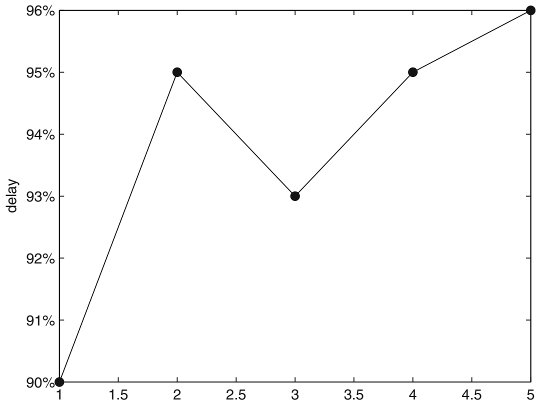

Fig. 11. The relationship between success rate and layers

5 Conclusion

A new method of cross-layer communication is proposed to deal with the high-latency, low-bandwidth and high-BER in UASNs, using cluster-based routing protocol. At MAC layer, it solves the collision between clusters and within cluster. At physical layer, nodes self-adaptively change transmission power and transmitting frequency to decrease energy. According to the simulation results, the proposed protocol achieves benefits in optimizing network performance.

References

1. Davis, A., Chang, H.: Underwater wireless sensor networks. In: 2012 IEEE Oceans, pp. 1–5 (2012)
2. Han, G.J., Jiang, J.F., Wan, L.T., Guizani, M.: Routing protocols for underwater wireless sensor networks. J. IEEE Commun. Mag. **53**(11), 72–78 (2015)
3. Han, G.J., Dong, Y.H., Guo, H., Shu, L., Wu, D.P.: Cross-layer optimized routing in wireless sensor networks with duty-cycle and energy harvesting. J. Wirel. Commun. Mob. Comput. **15** (16), 1957–1981 (2015)
4. Langendoen, K., Reijers, N.: Distributed localization in wireless sensor networks: a quantitative comparison. J. Comput. Netw. **43**(4), 499–518 (2003)
5. Jornet, J.M., Stojanovic, M., Zorzi, M.: On joint frequency and power allocation in a cross-layer protocol for underwater acoustic networks. J. IEEE J. Oceanic Eng. **35**(4), 936–947 (2010)
6. Jornet, J.M., Stojanovic, M., Zorzi, M.: Focused beam routing protocol for underwater acoustic networks. In: the Third ACM International Workshop on Underwater Networks, pp. 75–82 (2008)
7. Huang, C.B., Zheng, X.W., Gao, L., Yang, G.S., Zheng, J.C.: A centralized cross-layer scheduling protocol in UWSNs. J. Transducer Microsyst. Technol. **33**(10), 121–124 (2014)
8. Chen, Y.J., Wang, H.L.: Ordered CSMA: a collision-free MAC protocol for underwater acoustic networks. In: 2007 IEEE OCEANS, pp. 1–6 (2007)