An Efficient Geo-Routing Aware MAC Protocol for Underwater Acoustic Networks

(Invited Paper)

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Abstract. In this paper, we propose an efficient geo-routing aware MAC protocol (GOAL) for underwater acoustic networks. It smoothly integrates self-adaptation based RTS/CTS, geographic cyber carrier sense and implicit ACK to do combined channel reservation and next hop selection. As a result, it possesses the advantages of both geo-routing protocol and reservation based MAC protocol. Specifically, its self-adaptation based RTS/CTS, node can dynamically find out the best next-hop with low route discovery cost. In addition, through geographic cyber carrier sense, node can map its neighbors' time slots for sending/receiving DATA packets to its own time line, and thus the collision among data packets can be greatly reduced. With these features, GOAL outperforms geo-routing protocols. Plentiful simulation results show that GOAL provides much higher end-to-end reliability with lower energy consumptions than existing VBF routing with broadcast MAC protocol.

Keywords: underwater sensor network, geo-routing, MAC, self-adaptation, geographic cyber carrier sense.

1 Introduction

Underwater acoustic network is a promising technique that could connect underwater vehicles, sensor nodes and other devices working in an underwater environment via acoustic channels. It can be used to collect oceanographical data, monitor oceanic volcano activity or oil/gas field [1–3]. Although it is one class of ad hoc networks, the routing and MAC protocols for terrestrial ad hoc networks cannot serve it. This is because of its long signal propagation delay, narrow channel bandwidth, and high node mobility. Due to the same reasons, it is a big challenge to design efficient routing and MAC protocols for underwater acoustic networks [1–5].

In underwater acoustic networks, traditional routing protocols such as AODV [6] do not work here because of their intolerable costly route discovery process in long-delay underwater environments. Geo-routing protocols, such as VBF [7], VBVA [8] and DBR [9], are preferred here. These protocols do not need a dedicated route discovery and forward packets directly based on nodes' locations. Since location information is indispensable for many aquatic applications [10–14], these protocols do not cause much extra cost and are very efficient from the routing perspective.

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However, geo-routing protocols [7, 9] are usually based on the broadcast nature of the underlying acoustic channel. And it is highly possible that multiple nodes are selected as the next hop, which leads to collisions if all these next hop candidates relay the packet. Although the self-adaptation methods such as those in [7, 9] narrow down the size of the candidate set to some extent, the collision probability is still very high without proper medium access control(MAC) design and optimization.

Existing MAC protocols for underwater acoustic networks, such as R-MAC [15], UWAN-MAC [16] and T-Lohi [19], are usually based on channel reservations. In these protocols, senders and receivers interact with each other to reserve channel for data communications. And the sender/receiver pair must be known before the channel reservation process, which cannot be satisfied by current geo-routing protocols since a node cannot know its next-hop node before hand in the geo-routing protocol. For example, in R-MAC, a node reserves a channel by measuring the propagation delay and mapping the slot at the sender side to the receiver side, which is not compatible with the geo-routing protocol that cannot provide the next-hop information. Thus, a new MAC protocol which can effectively suppress collisions and can be smoothly combined with geo-routing protocol is highly desirable.

In this paper, we propose an efficient **G**eo-r**O**uting **A**ware MAC protoco**L** (GOAL) for underwater acoustic networks. GOAL smoothly integrates self-adaptation based RTS/CTS, geographic cyber carrier sense, and implicit ACK to find the next-hop node and to do channel reservation at the receiver side. Utilizing self-adaptation based RTS/CTS, forwarder can determine the best next-hop node with little route discovery cost. By adopting geographic cyber carrier sense, collisions among the data packets are almost eliminated. With implicit ACK strategy, control messages are significantly reduced and thus fewer collisions occur among control packets. With these techniques, GOAL is energy efficient and provides high end-to-end reliability. Another amazing feature is that GOAL can work in mobile underwater acoustic networks with localization services such as in [14].

The rest of this paper is organized as follows. Section 2 briefly discusses the related works. Then, GOAL is presented in detail in section 3. After that, simulation results and discussion are shown in section 4. At last, section 5 concludes and provides future works clues.

2 Background and Related Works

In this section, we will first review related works on geo-routing protocols in underwater acoustic networks and show disadvantages in collision resolutions. And then, we will review MAC protocols for underwater acoustic networks and their differences from our work.

In underwater acoustic networks, nodes communicate via acoustic channels and the propagation delay is pretty long, so it takes long time and lots of energy to do route discovery. As a result, geo-routing protocols which are based on nodes' location draw a lot of attention. VBF appears in [7]. In this protocol, packets are forwarded along the routing pipe from the source to destination. All nodes within the routing pipe will participate in the packet forwarding process. The authors in [9] propose a protocol based on the depth information where packets are forwarded to nodes with less depth. A new routing protocol based on VBF with void avoidance capability was proposed in [8]. For all these protocols, A node does not explicitly choose the next-hop but cooperates with its neighbors to determine the best relay node(s) according to some self-adaptation schemes.

The basic idea of self-adaptation is as follows. Whenever an eligible node gets a data packet, it starts to back off according to its location before forwarding the packet. Such a scheme can guarantee that a better relay node back off for a shorter time, so the best relay node ends back off and forwards data packet first. For example, as shown in Fig. 1, node B is closer to the vector from source node S to sink node D and also nearer to the sink node D than other neighbors of forwarder F. Thus, according to the self-adaptation scheme, the back off time of node B is shorter than that of node A after they receive the DATA packet from node F. As a result, node B first forwards the DATA packet. By overhearing the forwarding, other nodes, such as node A, cancel the back off and do not forward packet any more. In this procedure, several optimal relay nodes [1] can forward firstly and other nodes are suppressed by the overhearing the forwarding. While this procedure is repeated again and again, the packet gets closer to the sink node.

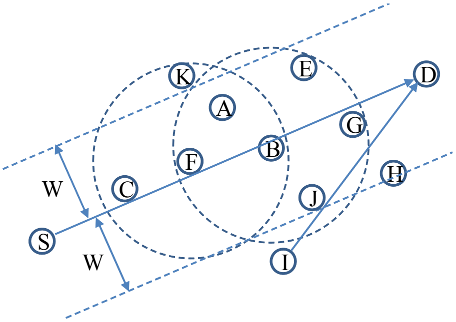

Fig. 1. Number of nodes vs. packet received ratio

Although such a self-adaptation scheme can improve the system's performance to some extent, it cannot prevent MAC collision when there are two or more adjacent nodes forwarding packets at the same time. As shown in Fig. 1, if node J happens to forward DATA packet for node I when B relays the DATA packet, collision might occur at the common neighbors of node B and J, and thus the DATA packet might not be further forwarded. This definitely harms the end-to-end reliability of the routing protocol. Also, the dropped packets waste plenty of energy, i.e., it is not energy efficient.

To further improve the performance of geo-routing protocol, effective collision resolution schemes should be employed, which are usually implemented in the MAC protocols. MAC protocols have been widely investigated for underwater acoustic networks in the last few years. In FAMA [17], RTS/CTS and carrier sense are combined to avoid collision. However, it is not energy efficient because the RTS/CTS packet is pretty long,

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[1] Some nodes might already forward the data packet before overhearing the forwarding by the best relay node.

which consume lots of energy. To improve the energy efficiency, in slotted FAMA [18], a modified FAMA, both control packets and data packets are sent at the beginning of a slot. In this way, the length of RTS/CTS packet is not determined by the maximal propagation delay as that in FAMA, so the energy is much more efficient. However, the RTS/CTS handshake requires routing protocol to provide the explicit next hop, i.e., it cannot be the MAC protocol for self-adaptation based routing protocol.

In T-Lohi [19], short tone message is used to reserve the channel to send data. However, even through a node does not receive any tone during a contention period, it cannot ensure that there is no collision at receiver side. In other words, it still suffers hidden terminal problem and cannot effectively avoid the collision. R-MAC appears in [15], which consists of three phases. In the first phase, each node measures the propagation delay to its neighbors. In the second phase, each node reserves receiving slot at the receiver side and then receiver confirms if the reservation is collision-free. This phase can make sure that there is no collision at receiver side for data packet. In the last phase, each node follows the reservation in the second phase to transmit data packet. Explicit receiver address is needed in phase two for the channel reservation, so it cannot work with self-adaptation based routing protocol. Unlike other reservation based MAC protocols, UWAN-MAC [16] does reservation via one way communication. Assuming the delay between neighbors does not vary, each node piggybacks the relative sending time of next packet in current packet. As a result, node knows when it will receive the next packet. However, such one way handshake cannot solve hidden terminal problem. Thus, collision is still heavy in multiple hop networks. In addition, UWAN-MAC requires node to foresee the exact sending time of next packet, which is unpractical in self-adaptation based routing protocols.

Different from above works, GOAL, the new approach in this paper, smoothly integrates self-adaptation scheme and MAC reservation techniques. First, it employs the self-adaptation scheme to do handshake and find the next hop. Similar to implicitly finding the best relay in self-adaptation based geo-routing protocol, the cost of selecting next hop is pretty low in GOAL. Also, the receiving slot is reserved based on the geographic information during the handshake, and then the DATA packet can be forwarded without collision. Thus, GOAL can avoid more collision while keeping a low route cost.

3 Description of GOAL

In this section, we will discuss our new geo-routing aware MAC protocol (GOAL), which is reservation based and can smoothly integrate with any known geo-routing protocols with self-adaptation. For instance, if GOAL adopts the self-adaptation scheme of VBF, it can be considered as a reservation based MAC protocol coupling with VBF. We first present the basic idea of GOAL. Then, we describe three key components of GOAL, Self-adaptation based RTS/CTS handshake, Geographic cyber carrier sense and Implicit acknowledgement. We apply the self-adaptation scheme of VBF to GOAL as a special case in the description to make it clear (Note that GOAL can be used with any self-adaptation scheme). After that, we will use one example to show the overall working process of GOAL with detailed analysis.

3.1 Basic Idea

GOAL is a reservation based MAC protocol. In GOAL, each node maintains a time schedule, which records the time slot corresponding to its neighbors' packet sending/receiving time. Whenever a node wants to send a packet, it should make sure that the selected sending time does not overlap with any existing time slot in the time schedule line. In this way, DATA packet can be made collision free. To map the sending/receiving slot to nodes' own time schedule line, self-adaptation based RTS/CTS handshake is employed where only a few qualified neighbors are allowed to reply a CTS packet to an RTS request, which will certainly reduce the collisions. The RTS/CTS handshaking process in GOAL is used to implement two-fold functionalities: determining the next hop and mapping neighbors' sending and receiving slot to node's own time schedule.

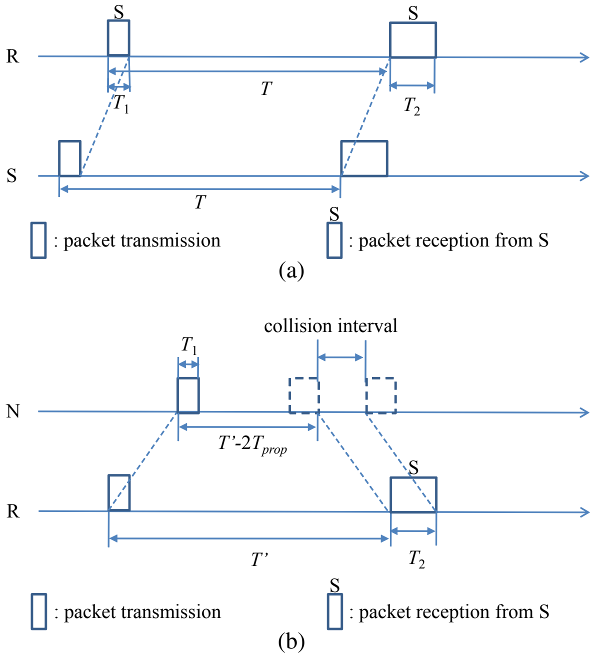

Fig. 2. (a) Mapping neighbor's sending slot, (b) Mapping neighbor's receiving time slot

As shown in Fig. 2(a), when sending a packet, node S piggybacks the transmission time T_2 and relative sending time T of the coming packet. After receiving this packet, node R can figure out the receiving time of the packet, i.e., it maps the sending time of the packet at node S to its time schedule line. Concretely, the interval between the time when node S sends the first and second packet is T. Assuming that the propagation delay between node R and S does not change much during the coming T time period, the interval between the time when node R begins to receive these two packets is still T. Therefore, after node R totally receives the first packet, it knows that it will receive next packet during time slot $[T - T_1, T - T_1 + T_2]$, where T_1 is the transmission time of the first packet. Note that the time slot is expressed by relative time and can be converted to absolute time easily.

Method of mapping receiving time is illustrated in Fig. 2(b). When node R sends the first packet, of which the transmission time is T_1, it notifies that it will receive the next packet T' time later. Suppose that node N knows that the propagation delay between it and node R is T_{prop}. After totally receiving the first packet, node R can find out that there will be a collision at node R if it emits any packet signal during $[T' - T_1 - 2T_{prop}, T' - T_1 - 2T_{prop} + T_2]$, where T_2 is the transmission time of the packet which node R will receive. Therefore, to avoid collision at node R, node N should make sure that the sending interval does not overlap with time slot $[T' - T_1 - 2T_{prop}, T' - T_1 - 2T_{prop} + T_2]$ when it sends out any packet.

Applying these two mapping schemes, node can map neighbor's sending and receiving time period to its time schedule line so as to avoid collision when transmitting DATA packet.

3.2 The GOAL Protocol

GOAL protocol consists of three parts: self-adaptation based RTS/CTS handshake, geographic cyber carrier sense, and implicit acknowledgement. As described in section 3.1, self-adaptation based RTS/CTS handshake and geographic cyber carrier sense are used to determine the optimal next hop and make channel reservation. In addition, implicit acknowledgement is imported to reduce the number of control message. The detail of these parts is provided as follows.

Self-Adaptation Based RTS/CTS Handshake. When current forwarder F intends to send out a data packet, it first selects a qualified sending time to broadcast a RTS$\{P_S, P_F, P_D, T, T_{DATA}\}$ packet. Via the RTS packet, node F tells its neighbors that it will send the DATA packet T [2] time later and the corresponding transmission time is T_{DATA}. It also provides the location of the source, current forwarder, and the destination: P_S, P_F, P_D.

After receiving RTS, neighbors of the forwarder get to know that they will receive the DATA packet $T - T_{RTS}$ time later, where T_{RTS} is the transmission time of RTS packet. Then, the neighbors of which the location is better than that of the forwarder start to back off according to the self-adaptation scheme of VBF. Once backoff terminates, the node sends the forwarder a CTS$\{P_{thisnode}, T', T_{DATA}\}$ packet, where $P_{thisnode}$ is the location of this node and T' is the relative time it will send DATA packet. Due to the broadcast feature of acoustic medium, part of node F's neighbors which is still in backoff state can overhear the CTS packet. Then, they cancel backoff because the CTS shows that there is a better relay. Finally, node F decides the next hop according to received CTS packets. If it does not receive any CTS, it waits for a random time and tries to resend the RTS. Otherwise, node F must receive at least one CTS from its

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[2] Note that T must be bigger than two times maximum propagation delay plus maximum backoff time, which is decided by the self-adaptation scheme. Otherwise, node F cannot determine the next hop before it sends DATA packet. In this case, node F will issue a new RTS for this DATA packet later.

neighbors. In this case, it sets next hop as the one with shortest adaptation time, which can be calculated by applying self-adaptation scheme again. Once the pre-scheduled DATA sending time comes, node F sends the DATA packet to the selected next hop.

As an improvement, multiple DATA packets to the same sink node can be transmitted in one packet train [18], so RTS/CTS handshake could do reservation for multiple DATA packets in one round. Obviously, this strategy can enhance the efficiency of handshake.

Geographic Cyber Carrier Sense. In underwater acoustic networks, it is difficult for node to avoid collision completely due to the long propagation delay. To address this issue, nodes in GOAL apply the two mapping methods in section 3.1 and utilize geographic information to mapping neighbors' packet sending and receiving slot to its time schedule line. Thus, the collision at neighbors can be greatly reduced if the selected packet sending time does not overlap with any slot in its time schedule line. This is so-called geographic cyber carrier sense.

Specifically, after receiving the RTS packet, node knows that it will receive the DATA packet during $[T - T_{RTS}, T - T_{RTS} + T_{DATA}]$ by applying method of mapping neighbor's sending time slot, where T_{RTS} stands for the transmission time of RTS packet. Then, this node converts the time slot to absolute time and inserts into its time schedule line.

CTS packet has two-fold functionalities: responding the RTS packet and notifying neighbors to avoid collision. On one side, with the CTS packet from node R, the sender of RTS knows that node R is a potential next hop. On the other side, based on the information in CTS packet, other neighbors of node R can evaluate the propagation delay T_{prop} between them and node R. The evaluation method is to use propagation speed to divide the Euclidean distance. Then applying the method of mapping neighbors' receiving time slot, this node gets that the there will be a collision at node R if it send packet during $[T' - T_{CTS} - 2T_{prop}, T' - T_{CTS} - 2T_{prop} + T_2]$, where T_{CTS} is the transmission time of CTS packet. To avoid collision, this node should not emit any packet signal during this period. Note that propagation delay measure method might introduce error because the acoustic signal is transmitted along bent way and the nodes are mobile. To tolerate the error, guard time T_{guard} is used, i.e., the propagation delay is in range $[T_{prop} - T_{guard}, T_{prop} + T_{guard}]$. Thus, the time period becomes $[T' - T_{CTS} - 2T_{prop} - 2T_{guard}, T' - T_{CTS} - 2T_{prop} + T_{DATA} + 2T_{guard}]$.

Based on geographic cyber carrier sense, nodes can obtain neighbors' sending and receiving schedule after RTS/CTS handshake. By recording the schedules in its time schedule line, node can conveniently choose a qualified time to send packet.

Implicit Acknowledgement. In terrestrial ad hoc networks, RTS/CTS/DATA/ACK can really improve the reliability of one hop transmission. In underwater acoustic networks, however, this scheme definitely causes more collisions among control packets because of low bandwidth and long propagation delay. A possible way is to adopt implicit acknowledgement scheme to reduce the number of control packets. Specifically, if the node which receives the DATA packet is not the destination, it must send RTS to determine the next hop within certain time. Because the previous hop is still within one hop range with a high probability, it can also overhear the RTS. Based on this heuristic rule, RTS is revised to include packet identifier (PID) of the DATA packet. As a result, the previous hop can confirm that the DATA packet is successfully forwarded.

For the destination node, it explicitly acknowledges the DATA packet using an ACK packet. In addition, a node will send explicit ACK packet without backoff if it receives a RTS when both of the following conditions are met: 1) the location of this node is better than the sender of RTS; 2) this node has received the DATA packet which RTS requests for.

For any node, if it does not receive an implicit acknowledgement or ACK packet within certain time after sending out the DATA packet, it will initiate a new RTS/CTS/DATA round to retransmit the DATA packet. Although retransmission can improve the transmission reliability, maximum times of retransmission should not be infinite because it introduces more delay and energy consumption. Thus, we define maximum retransmission times as a tradeoff. Specifically, one node can transmit and retransmit (both failure of receiving RTS and acknowledgement can cause retransmission) a DATA packet at most maximum retransmission times. If the maximum retransmission times is exceeded, the node should give up the DATA packet.

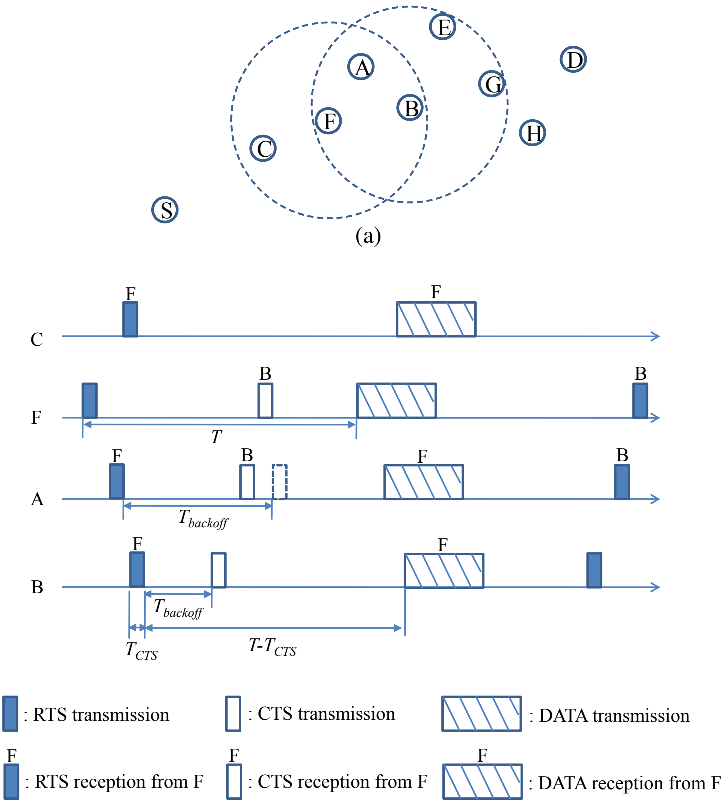
3.3 An Example of GOAL

In the example, the network topology is shown as Fig. 3(a). Node F now tries to forward the DATA packet from source node S to destination node D. Following GOAL protocol, node F selects a qualified sending time to broadcast a RTS$\{P_S$, P_F, P_D, T, T_{DATA}, $PID\}$ packet. Via the RTS packet, node F notifies its neighbors that it will send the DATA packet T time later and the corresponding transmission time is T_{DATA}. With the information in the RTS packet, node C, A, and B figure out that they will receive the DATA packet $T - T_{RTS}$ time later. Note that node C will not back off because its location is even worse than that of current forwarder node F, so these nodes except node C start to back off according to the self-adaptation scheme in VBF.

Same as VBF, since node B first ends backoff state, it sends CTS$\{P_B$, T', $T_{DATA}\}$ packet to node F. On one side, by overhearing the CTS packet from node B, node A realizes that there is a better relay, so it cancels the backoff. Also, based on the information in the CTS packet, node A can evaluate T_{BA}, which denotes the propagation delay between node B and node A. Thus, node A will not send any packet during time interval $[T' - T_{CTS} - 2T_{BA} - 2T_{guard}, T' - T_{CTS} - 2T_{BA} + T_{DATA} + 2T_{guard}]$. On the other side, node F finds out that the next hop could be node B after receiving the CTS packet. When the scheduled DATA packet sending time comes, node F sends DATA packet to node B since node B is the optimal one. Later on, node B tries to forward the DATA packet, so it sends RTS$\{P_S$, P_B, P_D, T, T_{DATA}, $PID\}$ packet to do handshake. Receiving this RTS packet, node F makes sure that the forwarding is successful and then prepares to forward other DATA packets.

3.4 Analysis of GOAL

In GOAL, nodes apply self-adaptation scheme in the RTS/CTS handshake to find the next hop. This procedure is similar to the normal self-adaptation based geo-routing protocol for data packet. Because RTS/CTS packet is much shorter than data packet, the



(a)

(b)

Fig. 3. (a) Network topology, (b) One hop forwarding

probability of collision among RTS/CTS packets in GOAL is much lower than that among data packets in self-adaptation based geo-routing protocol. Note that data packets in GOAL are almost collision-free owing to geographic cyber carrier sense, so the entire collision probability in GOAL is lower than that in self-adaptation based geo-routing protocol. As a result, GOAL could provide a higher end-to-end reliability than self-adaptation based geo-routing protocol.

As analyzed above, GOAL introduces MAC collision among short RTS/CTS while avoiding collision among long data packets. As a result, the collision probability is reduced. Note that the collision among long data packets wastes more energy than the collision among short ones, so GOAL requires less energy consumption for packet delivery than self-adaptation based geo-routing protocol.

To achieve above desirable features, however, GOAL incurs longer delay. As explained in section 3.2, nodes schedule the sending time of DATA packet T time later after sending the RTS packet, where T is at least two times maximum propagation delay plus maximum backoff time. Moreover, to use implicit acknowledgement, nodes also wait for more than one round trip. Furthermore, nodes in GOAL do retransmission if any failure occurs during the forwarding procedure, which also increase the delivery delay. Hence, the delivery delay in GOAL is higher than self-adaptation based geo-routing protocol.

4 Performance Evaluation

In this section, we use simulations to evaluate the performance of GOAL. Aqua-Sim [20], a NS-2 based underwater acoustic network simulator which is developed by the UWSN lab at UCONN, has been used for our simulations.

4.1 Simulation Settings

We simulate GOAL in a practical underwater scenario, which is abstracted from the application of monitoring gas/oil/oceanic volcano activity. Nodes are randomly deployed within a $300\times300\times500$m cubic area. Whenever a node detects an event, it will send the data collected to the sink node. To simplify the simulations, we make two assumptions: 1) a node can detect the event occurring within its sensing range; 2) event lasts for a long time [3], so nodes send data to sink node periodically as long as it can sense the event. The period is defined as sensing interval.

All node can move freely in horizontal two-dimensional space, i.e., in the X-Y plane. The speed of node follows an uniform distribution between 0.2 and 1.5 m/s. The transmission range is set to 120 meters. Sink node which is the destination for all data packets is fixed at (250, 250, 0). Nodes' sensing range is 80 meters. The size of data packet is 300 bytes. The maximum retransmission times is set to be 6. Each simulation last for 5000 seconds. The energy consumption parameters are based on a commercial underwater acoustic modem, UMW 1000, from LinkQuest [21]: the power consumption on transmission mode is 2 Watts; the power consumption on receive mode is 0.75 Watts; and the power consumption on sleep mode is 8 mW.

Three metrics are used to quantify the performance: packet delivery ratio, energy consumption per byte and delivery delay. Specifically, the packet delivery ratio is the ratio of the total number of packet sent by source nodes to the number of packet received by sink. The energy consumption per byte is to divide the total network energy consumption by the number of data bytes successfully received by the sink. The delivery delay is the average end-to-end delay of each packet received by the sink. We compare the performance of GOAL with VBF coupling with broadcast MAC (we use VBF for short in the rest parts) [7].

4.2 Simulation Results

Impacts of Data Sensing Interval. In this set of simulations, the number of nodes in the network is fixed to be 100 and we change the data sensing interval of every node from 20 to 70 seconds.

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[3] This is practical. For example, oceanic volcano usually belches slight smoke and ashes for a long time before it finally erupts.

As shown in Fig. 4– 6, GOAL can provide a high end-to-end reliability. Fig. 4 clearly show us that GOAL can provide much higher packet delivery ratio than VBF. This is because GOAL can greatly reduce collision by its RTS/CTS handshaking process and its channel reservation mechanism. In addition, we can see that the packet delivery ratio of GOAL increases while the sensing interval becomes larger. This is because nodes with a larger sensing interval generate less packets, which accordingly causes less collisions. Since the maximum retransmission times is fixed, the packet delivery ratio is improved when there are less collisions. We can also see that the packet delivery ratio of VBF does not vary much while the sensing interval increases. This is because VBF is best-effort and the collision probability of VBF mainly depends on the self-adaptation scheme, which is highly related to the node distribution. Note that the size of network is fixed and nodes are uniformly deployed. Hence, the node distribution is decided by node density. In this group of simulation, node density is fixed, so the packet delivery ratio nearly keeps the same value.

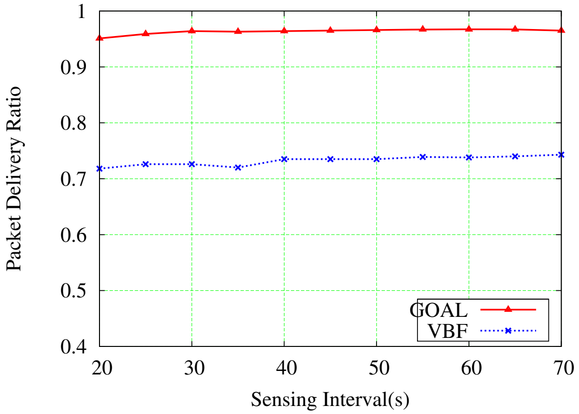

Fig. 4. Sensing interval vs. packet delivery ratio

GOAL can also achieve high energy efficiency. From Fig. 5, we can clearly see that GOAL is more energy efficient than VBF, especially when the sensing interval becomes larger. This is because in GOAL, when the sensing interval is shorter, multiple packets can be sent together with just one RTS/CTS handshaking, which can improve the system's energy efficiency. In addition, as the sensing interval becomes larger, less data packets is sent in the network. Thus, most nodes will waste its energy in the idle state with constant rate (8mw). This also increases the energy consumption when the sensing interval is larger.

Considering the reliability requirement, the energy consumption in VBF is much higher than that in GOAL. For example, let us set P_G as the delivery ratio of GOAL and P_V as delivery ratio of VBF. And set E_G and E_V as energy consumption of GOAL and VBF respectively. To achieve the same packet delivery ratio, VBF should do retransmission for N times in average and thus the energy consumption is NE_V, where N satisfies

$$1 - (1 - P_V)^N = P_G \tag{1}$$

Hence, N can be expressed as follows

$$N = log_{1-P_V}(1 - P_G) \tag{2}$$

In Fig. 4, for example, the packet delivery ratio of GOAL and VBF is approximately 0.97 and 0.73 when sensing interval is 50 second, respectively. Applying above equation, we can get the average times that VBF should transmit each packet to reach the same packet delivery ratio as GOAL as follows.

$$N = log_{1-0.73}(1 - 0.97) = 2.67 \tag{3}$$

Therefore, the energy consumption of VBF should be at least doubled. In other words, the energy consumption in GOAL is less than half of that in VBF, which indicates that GOAL is more energy-efficient.

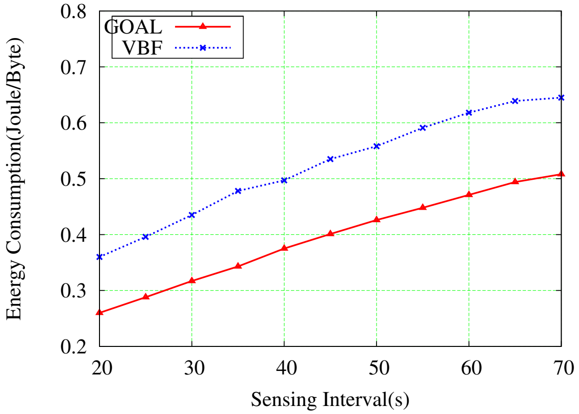

Fig. 5. Sensing interval vs. energy consumption

Fig. 6 shows us that the end-to-end delay of GOAL decreases with the increase of sensing interval. This is because collisions increase when sensing interval is shorter. With collisions, nodes have to initiate a new RTS/CTS/DATA round to do retransmission, which introduces extra delay. As the sensing interval becomes larger, less collisions and retransmission appear. Therefore, the delay decreases while the sensing interval increases. For VBF, which is a best-effort protocol, the delivery delay nearly has nothing to do with traffic rate, but is mainly decided by the backoff time in self-adaptation scheme. Thereby, the delivery delay in VBF almost does not change in Fig. 6.

Impacts of Node Density. In this set of simulations, we set the sensing interval of every node to be 50 seconds and change the number of nodes in the network from 70 to 120.

The impact of node density is shown in the coming three figures. In Fig. 7, we can see that the packet delivery ratio of GOAL is much higher than that of VBF. This is still because GOAL reduces more collision than VBF and VBF is best-effort. Also, we

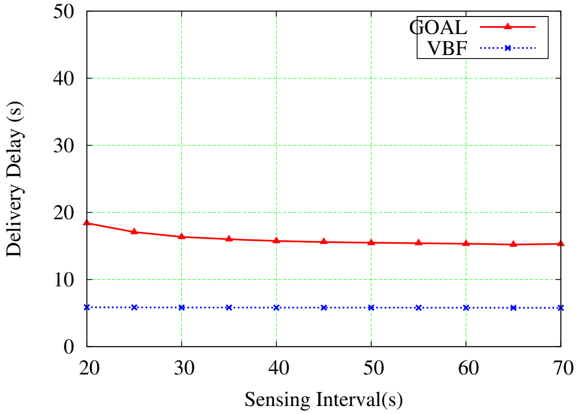

Fig. 6. Sensing interval vs. delivery delay

can see that the packet delivery ratio of both GOAL and VBF increases while there are more nodes within network. One reason is as mentioned before: GOAL largely reduces the MAC collision via doing reservation for DATA packet. The other reason it related to the self-adaptation scheme. When the node density is lower, there are fewer qualified next hops according to the self-adaptation scheme. Particularly, some forwarders do not have qualified next hop. For VBF, a best effort protocol, the DATA packet is definitely dropped in such case. In GOAL, forwarding failure can be detected by missing the implicit acknowledgement, and thus retransmission is issued.

From Fig. 8, we can see that GOAL consumes less energy than VBF for transmitting every unit data from source to sink. The reason is similar to that of Fig. 5. In VBF, the collision probability is higher than that in GOAL. Moreover, each collided packet in VBF wastes much more energy than that in GOAL because the packet in VBF is much

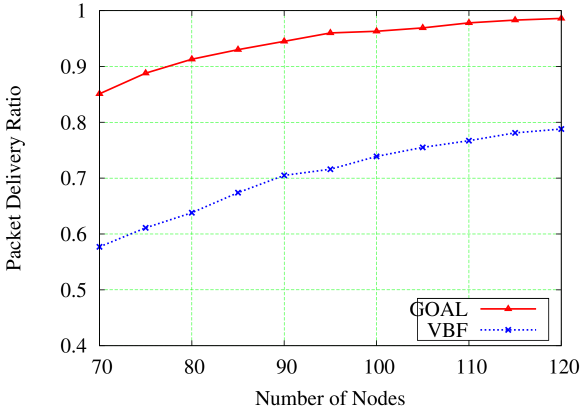

Fig. 7. Number of nodes vs. packet delivery ratio

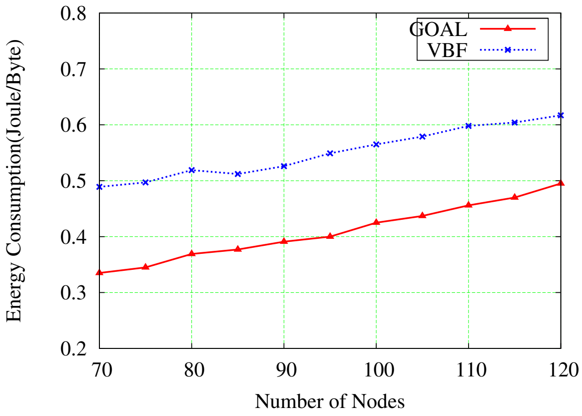

Fig. 8. Number of nodes vs. energy consumption

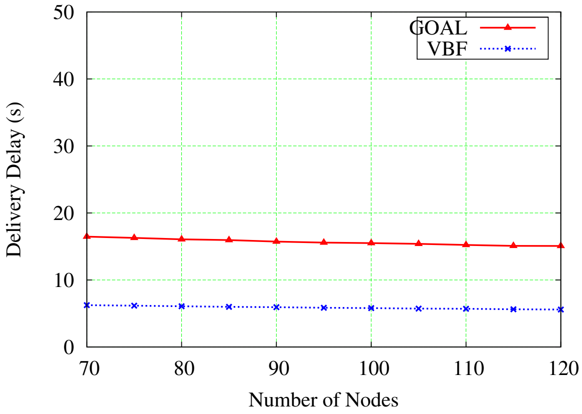

Fig. 9. Number of nodes vs. delivery delay

longer. As a result, GOAL saves more energy. Like the analysis for Fig. 5, if we analyze the energy consumption with same packet delivery ratio, we can see that the energy consumption in GOAL is much less than that in VBF, especially when there are less nodes within the network.

In Fig. 9, the delivery delay of GOAL is higher than VBF. The reason has been mentioned before: the handshaking and implicit acknowledgement in GOAL introduce more delay while VBF is a best-effort protocol which does not care whether the transmission to next hop is successful. Due to the same reason, the delivery delay of VBF is almost same in Fig. 9. Additionally, we can see that the delivery delay of GOAL slightly increases while the node deployment becomes dense. This is because dense deployment causes more collisions among the control messages. Thus, the retransmission times, which raises the delivery delay, are increased.

5 Conclusion

In this paper, GOAL, an efficient geo-routing aware MAC protocol is proposed for underwater sensor networks. It is a reservation based MAC protocol which can smoothly integrate with any existing geo-rouing protocols with self-adaptation capability. Self-adaptation based RTS/CTS handshaking, geographic cyber carrier sense and implicit acknowledgement are used in GOAL to improve system performance. Although the end-to-end delivery delay increases because of the hop-by-hop retransmission mechanism in GOAL, it can achieve high end-to-end delivery ratio with low energy consumption. Plentiful simulation results show that GOAL outperforms existing VBF with broadcast MAC in both end-to-end delivery ratio and energy efficiency.

References

1. Cui, J., Kong, J., Gerla, M., Zhou, S.: Challenges: Building Scalable Mobile Underwater Wireless Sensor Networks for Aquatic Applications. IEEE Network, Special Issue on Wireless Sensor Networking 20(3), 12–18 (2006)
2. Heidemann, J., Ye, W., Wills, J., Syed, A., Li, Y.: Research Challenges and Applications for Underwater Sensor Networking. In: Proceedings of IEEE Wireless Communications and Networking Conference, pp. 228–235 (2006)
3. Partan, J., Kurose, J., Levine, B.N.: A Survey of Practical Issues in Underwater Networks. In: Proceedings of ACM WUWNet (2006)
4. Liu, L., Zhou, S., Cui, J.: Prospects and problems of wireless communication for underwater sensor networks. Wireless Communications & Mobile Computing 8(8), 977–994 (2008)
5. Chitre, M., Shahabudden, S., Stojanovic, M.: Underwater acoustic communicatin and networks: Recent advances and future challenges. Marine Technology Society Journal 42(1), 103–116 (2008)
6. Perkins, C.E., Royer, E.M.: Ad hoc on-demand distance vector routing. In: Proceedings of IEEE Workshop on Mobile Computing Systems and Applications, pp. 90–100 (1999)
7. Xie, P., Cui, J., Lao, L.: VBF: Vector-Based Forwarding Protocol for Underwater Sensor Networks. In: Proceedings of IFIP Networking, pp. 228–235 (2006)
8. Xie, P., Zhou, Z., Peng, Z., Cui, J., Shi, J.: Void Avoidance in Three-Dimensional Mobile Underwater Sensor Networks. In: Liu, B., Bestavros, A., Du, D.-Z., Wang, J. (eds.) Wireless Algorithms, Systems, and Applications. LNCS, vol. 5682, pp. 305–314. Springer, Heidelberg (2009)
9. Yan, H., Shi, Z., Cui, J.: DBR: Depth-Based Routing for Underwater Sensor Networks. In: Proceedings of IFIP Networking, pp. 72–86 (2008)
10. Cheng, X., Shu, H., Liang, Q., Du, H.: Slient positioning in underwater acoustic sensor networks. IEEE Transactions on Vehicular Technology 57(3), 1756–1766 (2008)
11. Erol, M., Vierira, L.F.M., Gerla, M.: AUV-Aided localization for underwater sensor networks. In: Proceedings of International Conference on Wireless Algorithms, Systems and Applications (WASA), pp. 44–51 (2007)
12. Frampton, K.D.: Acoustic self-localization in a distributed sensor network. IEEE Sensors Journals 6(1), 166–172 (2006)
13. Zhou, Z., Cui, J., Zhou, S.: Localization for Large Scale Underwater Sensor Networks. In: Proceedings of IFIP Networking, pp. 108–119 (2007)
14. Zhou, Z., Cui, J., Bagtzoglou, A.: Scalable Localization Scheme with Mobility Prediction for Underwater Sensor Networks. In: Proceedings of IEEE INFOCOM, pp. 2198–2206 (2008)

15. Xie, P., Zhou, Z., Cui, J., Shi, Z.: R-MAC: An Energy-Efficient MAC Protocol for Underwater Sensor Networks. In: Proceedings of International Conference on Wireless Algorithms, Systems and Applications (WASA), pp. 187–198 (2007)
16. Park, M.K., Rodoplu, V.: UWAN-MAC: An Energy-Efficient MAC Protocol for Underwater Acoustic Wireless Sensor Networks. IEEE Journal of Oceanic Engineering 32(3), 710–720 (2007)
17. Fullmer, C.L., Garcia-Luna-Aceves, J.: Floor Acquisition Multiple Access (FAMA) for Packet-Radio Networks. In: Proceedings of ACM SIGCOMM, pp. 262–273 (1995)
18. Molins, M., Stojanovic, M.: Slotted FAMA: a MAC protocol for underwater acoustic networks. In: Proceedings of IEEE OCEANS, pp. 16–19 (2006)
19. Syed, A., Ye, W., Heidemann, J.: T-Lohi: A New Class of MAC Protocols for Underwater Acoustic Sensor Networks. In: Proceedings of IEEE INFOCOM, pp. 231–235 (2008)
20. Xie, P., Zhou, Z., Peng, Z., Yan, H., Hu, T., Cui, J., Shi, Z., Fei, Y., Zhou, S.: Aqua-Sim: An NS-2 Based Simulator for Underwater Sensor Networks. In: Proceedings of IEEE/MTS Oceans, pp. 1–7 (2009)
21. LinkQuest, `http://www.link-quest.com`