UMDR: Multi-Path Routing Protocol for Underwater Ad Hoc Networks with Directional Antenna

Jianmin Yang\textsuperscript{1,2}, Songzuo Liu\textsuperscript{1,2,*}, Qipei Liu\textsuperscript{1,2} and Gang Qiao\textsuperscript{1,2}

\textsuperscript{1}Acoustic Science and Technology Laboratory, Harbin Engineering University, Harbin 150001, China;
\textsuperscript{2}College of Underwater Acoustic Engineering, Harbin Engineering University, Harbin 150001, China

Email: *liusongzuo@hrbeu.edu.cn

Abstract. This paper presents a new routing scheme for underwater ad hoc networks based on directional antennas. Ad hoc networks with directional antennas have become a hot research topic because of space reuse may increase networks capacity. At present, researchers have applied traditional self-organizing routing protocols (such as DSR, AODV) \cite{1} \cite{2} on this type of networks, and the routing scheme is based on the shortest path metric. However, such routing schemes often suffer from long transmission delays and frequent link fragmentation along the intermediate nodes of the selected route. This is caused by a unique feature of directional transmission, often called as "deafness". In this paper, we take a different approach to explore the advantages of space reuse through multipath routing. This paper introduces the validity of the conventional routing scheme in underwater ad hoc networks with directional antennas, and presents a special design of multipath routing algorithm for directional transmission. The experimental results show a significant performance improvement in throughput and latency.

1. Introduction

In underwater ad hoc network, network nodes are typically equipped with omni-directional antennas. The omni-directional antenna is equally transmitting and receiving sound signals in all directions. Due to the nature of the broadcast, the conventional MAC protocol for ad hoc networks specifies that all nodes within the transmission range must suspend their possible transmission when a node is transmitting until the channel becomes idle again. These MAC schemes have a certain capacity limit for the network. With the recent progress in the research of "smart" or "adaptive" antennas, the directional transmission technology of underwater ad hoc networks has become possible. The
directional antenna divides the omni-directional transmission area into a fixed number of sectors, as shown in Figure 1. The transmission of a sector does not affect the signal propagation of other sectors. Thus, the space area previously occupied by an omni-directional transmission now can be shared by several directional transmissions. This feature is called "space reuse". While directional antennas have the potential to increase capacity and throughput of the network, they also cause new problems such as increased routing discovery overhead, complex MAC and routing protocols. For example, in directional transmission, the broadcasts require the same packet to be transmitted in all antenna elements in order. This may result in long media access delays and different receive times at different neighbor nodes. The routing specification also becomes more complex because each node needs to know not only the next hop, but also the antenna elements of the next hop. This means the networks would have longer routing messages and larger routing tables.

In this work, we try to study the impacts of directed transmission on the underwater ad hoc network routing scheme. In our study, a typical directional MAC (DiMAC) protocol [3] was used. Three routing schemes are proposed. First, we apply traditional dynamic source routing (DSR) protocols directly to DiMAC. Second, we introduce some necessary modifications to make the DSR more suitable for directional transmission, and the resulting protocol is called DDSR. Finally, we propose a new underwater multi-path directional antenna self-organizing route (UMDR) protocol, which could effectively utilize the advantages of spatial reuse and improve the routing performance.

2. Related Works

Although the application of directional antenna in wireless networks has been widely studied, the research in underwater ad hoc network is relatively limited, which is mainly limited by the media access control protocol and channel difference. Some studies of wireless networks routing schemes using directional antennas are reported in [3] [4] [5]. In [4], the authors use directional antennas to improve the efficiency of on-demand routing protocols in mobile ad hoc networks. The idea is to use directed replay during route rediscovery. In the traditional route rediscovery process, routing request is flooded the entire network once. However, in most cases, this flooded is unnecessary because the previous direction of the target node is known. In this paper, the author assumes that each node knows its direction for other nodes. When the transmission is corrupted, the rediscovery process sends routing requests only in the previous direction of the destination. In this way, you can reduce the overall routing overhead. In [5], directional antennas are used to improve routing performance in both cases. One is due to mobility and dynamic network division of the situation, the other is in the middle of the node caused by the movement of the route repair process. The proposed method takes advantage of the important characteristics of the directional antenna -longer transmission distance. In [3], a simple medium access control (MAC) protocol called DiMAC is proposed, and the DSR routing protocol is evaluated based on DiMAC. Some improvements have also been introduced to improve DSR performance for directional transmission. Because of the unresolved "deafness" problem, the authors conclude that the advantages of using directional antennas in self-organizing networks cannot be guaranteed, and in some cases it is better to use omni-directional antennas.

3. Antenna and MAC Models

The antenna model in our study consists of N beam patterns, as shown in Figure 1. We assume that the
main lobe of each beam has a conical radiation pattern of $2\pi / N$ radians. Antennas can work in both modes: omnidirectional and Directional. In directional mode, only one beam with $G_d$ gain can be used at a time, and in the omnidirectional mode, the signal is received with the gain of $G_o$. $G_d$ is inversely proportional to the number of beams used. The transmission distance of the antenna is proportional to the transmission gain. Thus, the directional transmitter can achieve a longer distance than the omni-directional transmitter at the same transmission power.

![Figure 1. Directional Antenna](image)

In our study, we used the DiMAC protocol as the MAC protocol. DiMAC is based on the IEEE 802.11 Distributed Coordination Function (DCF) and also uses RTS and CTS for channel reservation. In DiMAC, RTS / CTS packets are sent and received by directional antennas via a single specified antenna element. According to DiMAC protocol, three modules have been implemented based on 802.11 DCF:

1. The channel reservation mechanism for each antenna element. This includes the "send" and "receive" timers, and the NAV state for indicating the channel condition of the component and the packet sent / received.
2. Broadcast sweep function. The routing discovery phase requires broadcast. Some scans on some antenna elements may fail because these components may experience busy channels. There is a trade-off between retry attempts and routing discovery latencies. In our work, if the channel is busy, each element performs only one retry. Also, when the neighbor node receives the broadcast packet, it will not reply immediately because the sender may be sent through other antenna elements. The receiver must wait for a while to allow the sender to complete the scan.
3. Neighbor table. For single-hop transfer, the sender must know not only the next hop node, but also the antenna element of the next hop. To do this, we must create and maintain neighbor tables to update and find information related to each antenna element.

Deafness [6] is a unique and critical issue for directional MAC protocols such as DiMAC. As shown in Figure 2, when node A is communicating with node B through one of its antenna elements, it cannot hear (or cannot respond to) any signal from other elements. The problem is that DiMAC uses directional transmission to perform RTS / CTS switching between node A and node B. Therefore, any other node (for example, node C, node D or node E) is located in a different direction and will not hear the RTS / CTS channel reserved. If node C, node D or node E attempts to communicate with node A during data transmission with node B, no reply will be received before the timeout. After multiple retransmissions, node C, node D or node E will deduce that node A has been removed and any route of node A is broken. Obviously, this feature will affect MAC performance and routing performance.
4. Routing protocol description

Routing protocols in underwater ad hoc networks can usually be divided into two categories: reactive and active protocols. Most of the underwater ad hoc network routing protocols are reactive protocols. If the packet needs to be sent and no route is available to the destination, the reactive protocol performs route discovery. The reactive protocol achieves lower routing overhead at the expense of additional routing discovery cost.

Most of the existing routing protocols used for ad hoc networks select a single route for packet transmission based on the minimum number of hops. In this paper, we consider these traditional routing schemes to be ineffective for ad hoc networks with directional antennas. The main problem is the middle node deafness. More specifically, it is assumed that the data flow \( F \) is routed through the antenna element \( e \) of the active intermediate node \( N \). If node \( N \) frequently performs data exchange on other antenna elements, stream \( F \) will soon be subjected to link break element \( e \) due to excessive deafness of node \( N \). Traditional routing protocols will initiate expensive route rediscovery and data retransmission processes, although node \( N \) may become available for \( F \) soon. Deafness of all active nodes significantly increases the dynamics of the instantaneous topology of self-organizing networks. Its effect is even greater than mobility since switching from one antenna element to another may be very fast, and the duration of each session of the data exchange is very unpredictable. This poses a major challenge to the routing design of ad hoc networks with directional antennas.

We propose a reactive source routing protocol for underwater ad hoc networks using directional antennas. It is called underwater multi-path directional antenna self-organizing route (UMDR). In UMDR, each node maintains a routing table that lists the paths from the sender to each possible destination. Each node updates the routing table based on the overheard packet. A notable feature of UMDR is that the routing table records multiple routes to each destination, so when a route encounters a busy channel, it can immediately select an alternate route. The source node places the entire path in the packet header, and the intermediate node forwards the packet according to the path specified in the header. When there is a packet to be sent and there is no available route to the destination, the route discovery process is initiated.

During the route discovery process, the sender uses the sweeping mechanism to broadcast the routing request message. When a neighbor node receives a route request, it searches through its own routing table. If there is no available route to the destination, it will immediately rebroadcast the routing request over all its antenna elements, except that the antenna element which the message is
received. If it has an available route, it will send a routing reply message to the sender after a brief delay, which allows the sender to complete the scan. During packet forwarding, each node passes the message to the next hop based on the route specified in the packet header. If the first attempt fails, UMDR will try two more times. If all of these attempts fail, the UMDR assumes that the neighbor node is busy and immediately uses alternate routes. If the alternate route is not available or the cost of the hop count is much higher than the original route, the node will continue to use the original route until it assumes that the link is actually corrupted. The idea here is to forward the packet to the next hop as soon as possible. Due to the possible spatial multiplexing provided by the directional antenna, the chances of establishing alternative routes are much higher than those of the omnidirectional transmission environment. Multipath routing minimizes the delay per hop, effectively reducing overall end-to-end latency. Records the number of attempts for each next hop, and when it exceeds a certain threshold, the UMDR assumes that the neighbor node may have moved to another location. The scanning function of the neighbor table is executed to locate the neighbor node in the adjacent antenna element. If the scanning process fails, the broken link is assumed and the node performs route update.

The forwarding process requires an alternative route with the cost similar to the cost of the original route. This depends on the number of alternate routes stored in the intermediate node. In order to increase multi-pathing knowledge, the intermediate node can forward the old routing request if it comes from a different sender, or has a shorter length. This will definitely produce more routing packets, which increases the routing overhead. However, the advantage of this approach is that the destination and intermediate nodes can learn more disjoint routing. One of the characteristics of using directional antennas is the broadcast delay caused by broadcasting. Therefore, the first received routing request may not represent the shortest route [3]. In UMDR, the target node delays its routing reply in a short period of time, which may be equal to the scan delay. It can also send alternative routes at a reasonable routing cost.

As the directional antenna transmission distance is longer, so the network links are not easy to be destroyed. At the same topology change rate, the node may take a long time to move out of the neighbor’s range. However, in directed self-organizing networks, nodes may frequently move to adjacent antenna elements of the same node, especially when there are many antenna elements. This requires a switching mechanism. The handover function is implemented in the MAC protocol, where the location of the antenna elements of the neighboring nodes is periodically updated in the "neighbor table". For routing protocols, the handover and the actual link disconnection should be handled separately.

The routing tables and neighbor tables in the mobile node should be kept up-to-date. Each entry in these tables has a timer. Paused entries will be deleted in time. The antenna element entries in the neighbor table are updated when the switch occurs. When the link is disconnected, a "routing error" packet is generated. Any node that listens for this routing error packet will update its routing table based on the error message.

5. Simulation results and analysis
We check the performance of UMDR with the help of NS3. The simulation scenario is that of a 5 km by 5 km area, a total of 50 nodes are simulated. At the beginning, each node has a random initial position, and then it will move to the random destination at a randomly selected speed (evenly...
distributed between 0 and 10 m/s). When it reaches the destination, it will select another destination after a pause. In all scenarios, a send buffer with a size of 50 packets is maintained to store packets waiting for a route. The source node and the destination node are randomly selected from the network. All traffic contributes to network traffic, and its packet size is set to 512 bytes. 40 packets are used to test the overall performance. For fair comparison, simulate the same traffic and mobility scenarios for different protocols. Each data point is calculated as the average of 20 runs of different mobility scenarios.

Two metrics are used to test performance: delivery proportion and end-to-end packet delay.

1. Delivery proportion (DP) is the ratio of the number of received packets to the number of packets generated by the source node.

2. End-to-end packet delay based only on successfully forwarded packets. It includes routing delay, queuing delay for each intermediate node, contention delay for MAC layer, and transmission delay per hop.

There is a trade-off when selecting the number of antenna elements. Longer transmission distances can be achieved with more antenna elements with narrow beamwidths, but at longer scan delays, higher control overhead and more switching operations. The simulation is based on an eight-element antenna system.

The performance curves in Figures 3 (a) and 3 (b) represent the combination of three routes and MAC protocols: DSR over 802.11 DCF, DSR over DiMAC (DDSR), and UMDR over DiMAC.

Figure 3 (a) shows that DDSR and UMDR achieve higher packet delivery rate than DSR. There are two reasons. One is that the longer transmission range for directional transmission reduces the number of hops for the selected route. And also because the transmission distance is longer, routing errors and route rediscovery become less frequent. The routing overhead is reduced accordingly. Another reason is that the directional antenna reuses the space between the antenna elements, thereby increasing the channel capacity. UMDR uses multi-paths to further reduce the number of rediscover routes, and then increase the time fraction of sending packets to improve performance. UMDR also distinguishes between switching, busy and link disconnected, and performs different actions accordingly. This method effectively reduces the number of route discovery.

![Figure 3](image)

(a) Delivery Proportion

(b) End-to-End Delay (sec.)

**Figure 3.** Performance comparisons of three routing and MAC protocol combinations
Figure 3 (b) shows the average end-to-end delay of successfully delivered packets. The delay of DDSR and UMDR is shorter than DSR, but the improvement is limited. Several features of UMDR increase the end-to-end delay of packets. First, the scanning operations used in DDSR and UMDR will increase the broadcast time. Second, the destination has a delay after the routing request arrives. UMDR has better latency because at the intermediate node it does not wait for too many retries, but instead switches to alternate routes.

6. Conclusion
In this paper, underwater multi-path directional antenna self-organizing routing protocol (UMDR) is proposed. Some problems related to the effective routing in the directional antenna self-organizing network are solved, and the modification of the multi-path route of the directional antenna is introduced. Performance improvements show that directional antennas can actually improve the performance of underwater ad hoc networks through appropriate routing and MAC protocols.

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