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Key Technologies for Marine Information Networks

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Abstract. With the advancement of the strategy of ocean economy and ocean power, the construction of an integrated marine information network of air, sea, and water has become the core demand of the development of marine resources and modern maritime combat systems. This paper first reviews the development of a marine network, then focus on the protocol architecture of a marine information network, disassemble it into the maritime heterogeneous network and underwater hydroacoustic network, and evaluate the design scheme of medium access control (MAC) protocol in data link layer and routing protocol in network layer through literature analysis method and case study system. Then, a case study of cross-layer network architectures conducive to constructing marine information networks is presented. Finally, this study summarizes the shortcomings of the current research on marine network technologies and concludes that future network protocols are more inclined to be based on software-defined network (SDN) architecture incorporating lightweight deep learning models.

Keywords: Marine Information Network, MAC Protocol, Routing Protocols

1. Introduction

With the in-depth promotion of ocean economy and the concept of ocean power, the marine information network, which realizes three-dimensional sensing of the marine environment and full-area interconnection through the integration of unmanned platforms such as Autonomous Underwater Vehicles (AUVs), Unmanned Surface Vessels (USVs), Unmanned Underwater Vehicles (UUVs), and the reliance on multimodal transmission technology, such as satellite communication, hydroacoustic communication, optical communication, etc., is not only basic support for the digital development of marine resources, but also the It is not only the basic support for the digital exploitation of marine resources but also the core force of the new maritime combat system.

However, the currently developed marine information networks still have problems such as different physical layer technologies for aquatic and underwater networks, uneven network efficiency, complex channel modeling models, and the lack of cross-domain collaborative network protocol architectures [1]. Based on the above, this paper splits the marine information network into two important components, namely, the maritime heterogeneous network and the underwater hydroacoustic network, and analyses the network protocols used in the network layer and the data link layer respectively, and finally analyses the network architecture that is widely used in cross-domain communication, i.e., cross-layer design.

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2. Current status of research

The international research on cluster network technology in the single air and sea domain has been carried out earlier. In January 2017, the U.S. Navy released 103 "Mountain Quail" micro UAVs through the built-in bomb bay with three F/A-18F "Super Hornet" fighters at Mach 0.6 cruise state in complex electromagnetic environments [2]. The "Quail" micro UAVs are released through the built-in bomb bay to achieve autonomous formation and coordinated reconnaissance in the complex electromagnetic environment [2]. Between 1998 and 2010, the U.S. Army successively developed Seaweb98, Seaweb01, Seaweb03, Seaweb04, Seaweb08, Seaweb09, Seaweb10, as the largest and most representative of the underwater grouping, Seaweb in the number of underwater nodes, dynamic routing, centralised control of the nodes and other In April 2021, the U.S. Pacific Fleet for the first time jointly unmanned and manned ships to carry out air-sea cross-domain integrated combat exercises. 2018, the Shenyang Institute of Automation of the Chinese Academy of Sciences proposed air-sea three-dimensional coordinated observation technology and successfully completed experiments jointly with multiple departments in Dalian, and through the self-developed "Cloud Owl" unmanned helicopter, intelligent surface boat and underwater robot cluster, the first time to achieve the air-sea three-dimensional coordinated observation technology under weak communication conditions offshore, and the first time to achieve the "cloud owl" under weak communication conditions offshore, the first time in China. Through the self-developed "cloud owl" unmanned helicopter, intelligent surface boat, and underwater robot cluster, it is the first time to realize autonomous tracking of unmanned boats, dynamic target identification, and fusion of multi-platform accusation system in the offshore weak communication conditions [3].

3. Marine wireless communication methods

Efficient communication on the surface and underwater requires a combination of various marine wireless communication methods, and now the mainstream marine wireless communication methods are listed below:

(1) Hydroacoustic communication. Based on acoustic wave transmission, it has the advantages of low attenuation and long distance (kilometer level) and is the most mature technology underwater. However, due to the small speed of sound propagation in water, the channel noise interference is serious, resulting in a serious limitation of the bandwidth of hydroacoustic communication, and the multipath effect and Doppler effect have a greater impact on signal transmission.

(2) Optical communication. The use of a 450-530nm blue-green laser, supporting high-speed rate (Mbps level) directional transmission, is suitable for acoustic-optic link communication and cross-domain direct optical communication, but the scattering effect of seawater particles and the alignment problem also bring difficulties to the application of optical communication.

(3) Electromagnetic wave communication. The frequency band of electromagnetic waves as a carrier is mainly used in the land base station and the sea surface nodes between the communication and part of the underwater communication scene, but due to the electromagnetic wave itself anti-jamming ability is poor and the attenuation of the water medium to its role, the communication mode is not suitable for long-distance underwater communication.

(4) Magnetic induction communication. The use of mutual inductive coupling of the transmitting coil and receiving coil allows for the transmission of information, and the propagation rate is fast, with strong anti-interference ability, mostly used for cross-domain communication. Because the eddy current loss and the attenuation of the magnetic signal will increase with the increase of the

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signal transmission distance, so underwater magnetic induction communication is only suitable for medium and short distance transmission.

Since each type of communication has different propagation speeds, communication distances, and transmitting powers, it is possible to combine multiple physical layers to form multimode communications when constructing a network. To solve the problem of the incompatibility of network processing hardware and digital coding technology in multimode communication. Therefore, the researchers of the North Atlantic Treaty Organization (NATO) proposed the Janus communication standard. Using FH-BFSK coding, when nodes communicate for the first time using the Janus standard to complete the parameter negotiation, the device can be switched to other modulation schemes to achieve higher data rates and more efficient communication. Petroccia, R et al. designed the Automatic Identification System (AIS) based on the Janus standard service in a real marine environment, in which a gateway buoy collects AIS data from a ship, encodes it with the Janus standard, and successfully propagates the data to other underwater nodes such as submarines [4].

4. Offshore heterogeneous network protocol design

The maritime heterogeneous network unites a variety of communication technologies, using communication means such as satellite communication, radio communication, optical communication, and nodes such as ships, buoys, base stations, and UAVs to form a heterogeneous network aimed at achieving interconnection between different nodes at sea. The following section focuses on the data link layer protocols and network layer protocols of this network.

4.1. MAC layer design

The medium access control (MAC) protocols for maritime heterogeneous networks are classified in the same way as the MAC protocols for underwater networks, but maritime heterogeneous networks have diverse node types and higher densities, which place a greater demand on the network's multi-technology convergence, dynamic topology adaptation, and high-bandwidth transmission capabilities.

Huang et al. proposed a CSMA/CA-based adaptive MAC protocol, FMAC, to cope with the high density and high dynamics of flying self-organizing networks [5]. The Collective Neighbourhood Potential (CNP) is calculated and the CNP values of the same neighbors are predicted using the dynamics equations of the UAV. If the actual CNP is less than the predicted value, it means that the density of neighboring nodes becomes higher and the contention window (CW) will be increased. To solve the problem that a single MAC protocol cannot present better characteristics in complex heterogeneous networks, many scholars have proposed inter-protocol adaptive MAC protocols that unite multiple MAC protocols. Rhee et al. proposed a Z-MAC protocol that fuses CSMA and TDMA. When the channel is at a low contention level, the CSMA protocol is used and the nodes can contend for all the time slots; when the channel is at a When the channel is at high competition level, the TDMA protocol is used and nodes can only compete for the current time slot, which greatly improves the channel utilization [6].

4.2. Network layer design

In maritime heterogeneous networks, acoustic signals, optical signals, and radio frequency signals have different physical propagation mechanisms and channel characteristics, which means

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there are multiple transmission paths between source and destination nodes, and there may be multiple links between neighboring nodes consisting of different communication modes. Thus maritime heterogeneous networks can be modeled as multipath problems.

Existing multipath routing algorithms for heterogeneous communication networks include the more traditional static network-based Equivalent Multipath Routing Algorithm (ECMP) and Weighted Multipath Routing Algorithm (WCMP), as well as Dynamic Network-based Destination Sequence Distance Vector Protocol (DSDV) and On-demand Planar Distance Vector Routing Protocol for Wireless Self-organising Networks (AODV). Among them, Ye et al. et al. proposed W-ECMP, which dynamically calculates path weights using link utilization, replaces the hash algorithm with a probabilistic model, and splits long streams using the flowlet technique, which dynamically allocates sub-streams in conjunction with path states. This routing algorithm reduces FCT by 10% compared to ECMP [7]. Liu proposed the HAODV hybrid routing algorithm, which introduces a repair region. When the link is interrupted, the node can broadcast the repair request within the repair region to find an alternative path. Compared to the AODV algorithm, which requires retransmission, the HAODV algorithm does not require the intervention of the source node during the repair process, and the repair time is reduced to the tens of milliseconds level [8]. In addition to the more traditional routing algorithms, there are reinforcement learning methods based on CNN or GNN.H. V. B K et al. et al. proposed a route optimization method for LEO satellite networks using the DQN reinforcement learning algorithm, which guides the learning process through a reward function that considers network performance metrics such as latency, packet loss rate, etc., and integrates the available network resources, traffic demands and QoS requirements to achieve dynamic and efficient routing decisions [9].

5. Underwater hydroacoustic network protocol architecture

Due to the unique advantages of hydroacoustic communications underwater, underwater networks rely primarily on hydroacoustic communications technology. The hydroacoustic communication network mainly consists of underwater fixed nodes carrying hydroacoustic communication machines and underwater vehicles (AUVs). Referring to the OSI model and TCP/IP model proposed by the International Organisation for Standardisation, the hydroacoustic communication network is mainly composed of the physical layer, link layer, and network layer, and the following discussion focuses on the data link layer protocols and network layer protocols of this network.

5.1. MAC

The MAC protocol at the data link layer is mainly responsible for the rational allocation of network resources to the nodes to avoid problems such as packet collisions.MAC protocols can be classified into fixed allocation class, random competition class, and hybrid class.

Fixed allocation MAC protocols refer to the fixed allocation of channel resources to nodes, such as TDMA with different time slots, FDMA with different frequencies, and CDMA with different code types. Due to the small available bandwidth for hydroacoustic communication, the way FDMA divides the available frequency band into smaller bands is not applicable in practical communication. CDMA, which does not require time synchronization, requires additional control of the output power of each node to prevent the near and far effect, which is less applicable in aquatic acoustic communication networks with a high density of nodes. Wang optimized the time slot scheduling scheme for the TDMA protocol based on a minimum power transmission interference

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model and an underwater multi-hop mesh-type network, which improves the network's immunity to interference and optimizes the network's throughput and energy consumption [10]. Random competition class MAC protocols mean that nodes need to compete to obtain channel resources and are divided into random access class MAC protocols and handshake protocols that solve the channel allocation problem through handshake mechanism, which are further divided into ALOHA protocols that do not need to consider the channel resources and transmit data when available, and CSMA protocols that listen to the channel state. Guo et al. proposed an estimation of energy efficiency and network latency of the traffic adaptive TERI-MAC protocol. Unlike the traditional source node-initiated data request, TERI-MAC is initiated by the receiver based on the traffic estimation result, which reduces unnecessary data polling while improving the handshake efficiency and reducing the network latency [11]. Hybrid class MAC protocol is a MAC protocol that combines two protocols and can take advantage of each protocol. Pan proposed an LBTSA protocol that combines TDMA and CSMA/CA, which first allocates time slots reasonably according to the network load, and then selects the optimal access scheme for the master node according to the priority of the slave nodes to maximize the network throughput [12]. Mixed-class MAC protocols can bring out the advantages of different protocols, but they also bring considerable overhead to the network.

5.2. Network layer

Routing protocols at the network layer are responsible for planning transmission paths for packets to avoid problems such as path blockage. Due to problems such as prolonged hydroacoustic propagation and high attenuation, the routing protocols for UWSNs must comprehensively optimize network parameters such as delivery rate, energy overhead, and delay.

The more traditional routing protocols for current UWSNs are node location-based routing protocols and routing protocols that do not require location collection. Routing protocols based on node positioning information are vector-based forwarding (VBF), hop-by-hop vector-based forwarding (HH-VBF), focused beam routing (FBR), and directional flooding-based routing (DFR). Routing protocols that do not require the collection of node location information are Depth-Based Routing (DBR), Energy Efficient Depth Routing (EEDBR), and Directed Depth Routing (D-DBR) [13]. And deep learning methods that take Quality of Service (QoS) as an optimization objective have become a hot research topic. For example, Fu integrates Q-Learning and EEDBR protocols and introduces energy and depth constraints in the reward function, but the frequency of policy updates needs to be controlled by a time threshold to reduce energy consumption [14].

6. Cross-layer design

Traditional network adopts layered architecture, each layer focuses on solving a certain part of the information transmission process, such an architecture is convenient for the operation and maintenance of the network, but each layer of the network works alone and cannot schedule other networks, which is not conducive to the combination of maritime heterogeneous networks and underwater hydroacoustic networks. Due to the introduction of multimode communication in marine IoT, the data rate and transmit power of each communication mode are different, which leads to different working statuses of the physical layer, data link layer, and network layer when transmitting signals, which undoubtedly increases the burden of the traditional layered network that can only transmit information between neighboring layers. The cross-layer design allows the exchange of information parameters between different network layers and coordinates the transmission strategies of different layers by jointly considering the operating states of multiple network layers to improve

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the network throughput and maximize network resources. Murtaza, C et al. designed an IEEE 802.15.6 MAC protocol based on CSMA/CA, which decides whether a node is to send data; if the channel is not idle, then the node is waiting, and the node that listens to the idle state is given priority to send data [15]. Zhang et al. proposed an opportunistic routing algorithm applied to underwater acoustic-optic networks, which unites the physical layer and the network layer, first broadcasts the location and number of neighboring nodes omnidirectionally over the acoustic link and selects the optimal sector, and then sends the data quickly to the next hop using the optical link to the next node [16].

7. Conclusion

Most of the existing network experiments use simplified models or water tanks to simulate the actual marine environment, however, the marine environment is complex and variable, waves, bubbles, ocean depth, and other influencing factors will make the channel on the marine information network, in addition to the network in the sea and air in the two mediums of the transmission of information to the channel modeling also brings no small difficulty. The method of establishing a channel standard library for various typical channels may provide a direction for accurate channel modeling.

The application of AI algorithms in network protocol architectures with strong adaptive capability and topology optimization has achieved good results in various simulation experiments and small-scale sea trials. However, if applied to large-scale marine information networks with high node mobility, how to ensure the QoS of the network under the environment of reduced network overhead, low energy consumption and limited arithmetic power will become a key issue. The software-defined network (SDN) architecture that separates the control plane has powerful programmability and scalability, and is an excellent architecture for implementing artificial intelligence algorithms. This thesis mainly discusses the architecture and network protocols of the data link layer and network layer of the marine information network and lacks an in-depth discussion of the physical layer of the network, failing to show in detail the important multimode communication technology in the marine network. How to design SDN network architecture and develop low energy efficient AI algorithms will become a mainstream research direction.

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