Hybrid Satellite-Terrestrial Communication Networks for the Maritime Internet of Things: Key Technologies, Opportunities, and Challenges

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Abstract—With the rapid development of marine activities, there has been an increasing number of maritime mobile terminals, as well as a growing demand for high-speed and ultra-reliable maritime communications to keep them connected. Traditionally, the maritime Internet of Things (IoT) is enabled by maritime satellites. However, satellites are severely restricted by their high latency and relatively low data rate. As an alternative, shore & island-based base stations (BSs) can be built to extend the coverage of terrestrial networks using fourth-generation (4G), fifth-generation (5G), and beyond 5G services. Unmanned aerial vehicles can also be exploited to serve as aerial maritime BSs. Despite all of these approaches, there are still open issues for an efficient maritime communication network (MCN). For example, due to the complicated electromagnetic propagation environment, the limited geometrically available BS sites, and rigorous service demands from mission-critical applications, conventional communication and networking theories and methods should be tailored for maritime scenarios. Towards this end, we provide a survey on the demand for maritime communications, the state-of-the-art MCNs, and key technologies for enhancing transmission efficiency, extending network coverage, and provisioning maritime-specific services. Future challenges in developing an environment-aware, service-driven, and integrated satellite-air-ground MCN to be smart enough to utilize external auxiliary information, e.g., sea state and atmosphere conditions, are also discussed.

Index Terms—Maritime communication network, maritime channel, maritime service, satellite-air-ground integration, knowledge library.

I. INTRODUCTION

Maritime activities, such as marine tourism, offshore aquaculture, and oceanic mineral exploration, have developed rapidly in recent years. With the increasing number of vessels, offshore platforms, buoys, etc., there has been a growing demand for high-speed and ultra-reliable maritime communications to keep them connected [11]. For example, navigational information and operational data are required for the safe navigation of all vessels, and multi-media communication services are needed for the entertainment of passengers, crew, and fishermen onboard. Offshore drilling platforms require real-time operational data communications, and the buoys have a large amount of meteorological and hydrological data for uploading [2–4]. Particularly, for maritime rescue, in addition to information exchanges using texts and voice, real-time video communications are often required to achieve better coordination between ships and between ship and shore [5]. Therefore, building a broadband maritime communications network (MCN) for the maritime Internet of Things (IoT) is of great significance for marine transportation [6,7], production safety [8] and emergency rescue [9].

Currently, maritime mobile terminals mainly acquire communication services via maritime satellites, or through base stations (BSs) on the coast/island. Narrow-band satellites, represented by International Maritime Satellites (Inmarsat), mainly provide services such as telephone, telegraph, and fax, and their communication rate is low. The annual throughput of Inmarsat is 66 Gbps in 2016, while the number of ships has exceeded 2 million, and the average communication rate for each ship is less than 33 kbps [10]. In order to meet the demands for broadband satellite communication services, several countries have launched expensive high-throughput satellites, such as the EchoStar-19 in the United States. In addition to maritime satellites, shore & island-based BSs can be built to extend the coverage of terrestrial 4G/5G networks for maritime activities [11]. The existing shore-based communication systems, represented by the Navigation Telex (NAVTEX) system and the Automatic Identification System (AIS), mainly provide services, such as information broadcasting, voice, and ship identification, but cannot provide high-speed data services [12]. In order to improve the communication rate, several companies, such as Huawei and Ericsson, have carried out long-distance shore-to-ship transmission tests based on Worldwide Interoperability for Microwave Access (WiMAX) or Long Term Evolution (LTE) networks [13,14]. However, the coverage of these systems is limited by the earth curvature and maritime environment. To enhance offshore coverage, Singapore has planned to build a mesh network through ship-to-ship interconnections, and unmanned aerial vehicles (UAVs)
can also be exploited to serve as aerial maritime BSs [15].

Despite all these approaches, there are still open issues towards the establishment of an efficient hybrid satellite-terrestrial MCN. Different from terrestrial communications for urban or suburban coverage, the MCN faces several challenges, due to the complicated electromagnetic propagation environment, the limited geometrically available BS sites, and rigorous service demands from mission-critical applications [16]–[22].

Compared with the terrestrial environment, the atmosphere over the sea surface is unevenly distributed due to the large amount of seawater evaporation. Shore-to-ship and ship-to-ship communications are much more susceptible to both sea surface conditions such as tidal waves, and atmospheric conditions, such as temperature, humidity, and wind speed. Besides, the height and the angle of ship-borne antennas vary rapidly with the ocean waves. The fading of maritime channels is particularly sensitive to parameters, such as antenna height and angle, which may cause frequent link interruption. Therefore, the transmission efficiency in maritime scenarios is often low, due to these complex time-varying factors.

Satellite communications are less susceptible to maritime environment than shore-to-ship-to-ship communications. The integration of satellite and terrestrial systems can improve communication reliability and expand the coverage of MCNs. However, due to the limited onshore BS sites, and the strong mobility of the ship-borne BSs, aerial BSs, and low-earth orbit (LEO) satellites, the topology of the hybrid satellite-terrestrial MCN is highly irregular. There always exist blind zones in the planned coverage area. Besides, when a BS covers remote users with high power, it will generate strong co-channel interference to the nearby users served by neighboring BSs. The coverage performance of MCNs is still restricted by the existence of blind zones and areas suffering from severe interference.

Besides, marine information construction involves industries such as maritime affairs, fisheries, ports, shipping, and coastal defense. The maritime application scenarios are quite different, and their service requirements are unique. To provide reliable services for various maritime-specific applications is a major challenge for the MCN. It is also important to effectively allocate spectrum and power resources based on the characteristics of different service requirements.

To tackle with the above-mentioned challenges, a number of studies have been conducted in academia and industry. To enhance the maritime transmission efficiency, various channel measurement and modeling projects have been conducted to analyze the impact of important system parameters (frequency, antenna height, etc.) and maritime environments (sea state, weather conditions, etc.) on the maritime channel fading. Besides, more advanced resource allocation schemes, such as dynamical beamforming and user scheduling techniques, have been studied to utilize the dynamic changes in maritime channels. In addition, several studies have exploited the evaporation duct effect to improve the transmission efficiency, especially for remote ship-to-ship/shore transmission. To expand the network coverage, various BSs have been utilized, including onshore BSs, ship-borne BSs, aerial BSs, and satellites. For a BS, more advanced transmission techniques, such as beamforming and microwave scattering, have been studied to reduce the signal attenuation and extend the coverage. In addition, anti-interference and satellite-terrestrial coordination schemes have been studied to overcome the complex interference due to the irregular network topology. To satisfy the unique maritime service requirements, different systems and their transmission and resource allocation techniques have been studied for different service requirements, such as bandwidth, latency, and criticality.

Although there are a large number of papers on the above studies, the number of survey papers on MCNs is still limited. Besides, most of them focused on certain issues, such as channel models [16]–[17], network management [18], and existing systems [19]–[22]. On the other hand, the survey papers on some hot topics, such as 5G channel measurements and models [23] and space-air-ground integrated networks [24], could provide some inspirations for the development of an efficient hybrid satellite-terrestrial MCN, but they did not specially focus on maritime scenarios. To the best of the authors’ knowledge, a survey paper for hybrid satellite-terrestrial MCNs covering various and the latest technologies and presenting the opportunities and challenges is still missing.

To fill in the gap, this paper provides a survey on the demand, state of the art, major challenges and key technical approaches in maritime communications, as depicted in Figure 1. In particular, focusing on the unique characteristics of maritime communications compared with terrestrial and satellite communications, it discusses the major challenges of MCNs from the perspectives of physical and geographical environments, as well as service requirements, and illustrates the corresponding solutions. Finally, it also suggests developing an environment-aware, service-driven and satellite-air-ground integrated MCN, which should be smart enough to utilize the external auxiliary information, e.g., the sea state conditions.

The remainder of this paper is organized as follows. In Section II, the ever-increasing demand for maritime communications is introduced in terms of rate, latency and criticality. Section III briefly reviews and discusses the state-of-the-art MCNs, including satellite-based, shore-based, island-based, vessel-based, and air-based MCNs. In Section IV, we introduce the key technologies that can be used to enhance maritime transmission efficiency, including maritime channel measurements and models, the use of evaporation duct, and efficient resource allocation. Section V introduces the key technologies to extend the coverage of MCNs, such as multi-hop wireless networking, high-throughput satellites and satellite-terrestrial cooperation, microwave scattering, and dynamic beam scheduling. The key technologies for providing maritime-specific services, including mission-critical and secure communications, multimedia and content distribution services, and intelligent transportation services, are discussed in Section VI. In Section VII, we suggest the architecture and features of future smart MCNs, as well as suggesting future research topics. Section VIII concludes this paper.
II. DEMAND FOR MARITIME COMMUNICATIONS

The demand for maritime communications emerged in the early 20th century. With tragedies of various maritime accidents, such as the sinking of the Titanic in 1912, the maritime community awakened to the need for maritime communications in the event of search and rescue, to ensure the safety of ships and lives on the sea. In 1914, the International Convention on the Safety of Life at Sea (SOLAS) was developed. It mandates that ships sailing at sea must have battery-powered transceivers for transmitting and receiving radio alarm signals [25]. In that era, maritime communications played an important role in distress communication and rescue. In this case, low-speed maritime communication services were enough to meet the demand for emergency rescue.

The number of maritime activities has increased dramatically since the beginning of the 21st century, with the development of the world’s economies and the prosperity of the modern shipping industry. Maritime activities, such as marine tourism, offshore aquaculture and oceanic mineral exploration, have brought about a growing demand for high-speed and ultra-reliable maritime communication services. For example, the annual throughput of communication services provided by maritime satellites was less than 5 Gbps in 2005, while this number increased to about 66 Gbps in 2016 [10].

In industrial applications, marine informatization management requires wireless data services, such as video surveillance, video conferencing, and navigational data services. Other marine industries, such as marine fisheries and offshore oil exploration, also have a large amount of data for uploading. For marine tourism applications, multimedia services are needed to satisfy the passengers and the crew, and Internet services are required to keep them connected at any time. For the applications described above, high-speed and low-cost maritime communications are required [2]–[4].

For maritime rescue, real-time and high-reliability maritime communication services are required to enable coordination between ships and between ship and shore. In addition to information exchanges using texts and voice, real-time video communications will be very helpful for conducting rescue operations in a more accurate manner. Real-time and high-reliability services are also required for maritime military applications, e.g., for communication and coordination between warships and between fleets and land. Besides, military communications require a higher level of security to prevent the data transmission from being intercepted by eavesdroppers [26]–[28].

According to the nature of the communication network organization and service demands, maritime communication services can be classified as secure communications, dedicated communications and public communications [12]. Secure communications include voyage reports and severe weather warnings to ensure safe navigation, as well as communications for help, search and rescue in the event of a shipwreck. Dedicated communications allow the navigation department or the maritime enterprise to establish internal communication protocols, and set up communication links between a self-designed or leased coast station and its own ships according to the application requirements. Public communications refer to the communications between ship personnel, passengers, and any users of the land-based public communication network [29].

Typical maritime communication services are depicted in Figure 2, according to their requirements for rate and latency [30]. Navigational and operational communication services, such as ship reporting, voyage reporting, electronic navigational chart (ENC) updates, coast state notification, and environment notification, are required by all vessels. These services do not require much bandwidth, and can be provided by coast stations or maritime satellites [31] [32]. Secure communications services, e.g., for emergency rescue and military missions, have a critical demand for latency. There have been increasing demands for real-time video communications
Fig. 2. Typical maritime communication services.

instead of voice services in such mission-critical maritime activities \cite{33}–\cite{35}. Dedicated communications usually have a higher demand of bandwidth, with tolerance for high latency. The demands for dedicated services keep increasing with the development of maritime industries, such as marine monitoring and maritime oil exploitation. Public communications, such as web browsing and video downloading services, are mainly for passenger and crew infotainment. For public communications, a great deal of bandwidth is required, while the demand for latency varies from real-time to minutes. The demands for maritime public communications have grown explosively, and will continue to increase with the development of maritime tourism, as well as smartphones. From the above, the maritime application scenarios are quite different, and the service requirements are also unique. To provide such diversified services of high rate, low latency and high reliability for different applications within one network is a major challenge for MCNs. In this case, effective resource allocation and efficiency in spectrum and energy are very important.

III. STATE-OF-THE-ART MARITIME COMMUNICATIONS

Maritime communications began at the turn of the 20th century, pioneered by Marconi’s work on long-distance radio transmissions. In 1897, Marconi established a 6-km communication link across the Bristol Channel, which is the first wireless communication over open sea. In 1899, he realized the transmission across the English channel, from Wimereux, France to Dover, England, about 50 km away. In the same year, Marconi and his assistants installed wireless equipment on the Saint Paul, a trans-Atlantic passenger liner, and successfully received telegrams from the coast station 122 km away. In 1901, Marconi achieved trans-Atlantic communications with a transmission distance of over 3000 km, using a 20 kW high-power transmitter and a 150-meter-high receiving antenna \cite{36}–\cite{38}. Marconi’s experiments aroused great interest in the shipping industry of Europe and North America. From then on, many countries began to install coast stations and ship-borne radio stations, including many small stations, and a few large stations equipped with high-power transmitters and high-sensitivity receivers. Narrowband communication services were provided, such as telegraph, telephone, fax and data transmissions via intermediate frequency (MF), high frequency (HF), very high frequency (VHF), ultra high frequency (UHF) bands \cite{39}–\cite{41}.

At present, several projects and research have been conducted on broadband MCNs. Norway and Portugal launched the MARCOM project and the BLUECOM+ project, respectively, to provide broadband communications for remote areas through the joint use of Wireless Fidelity (Wi-Fi), General Packet Radio Service (GPRS), Universal Mobile Telecommunications System (UMTS), and LTE technologies \cite{42}–\cite{45}. Singapore launched the TRITON project, where a wireless multi-hop network is formed between adjacent vessels, maritime beacons, and buoys, to ensure wide-area coverage \cite{46}–\cite{48}. In addition, the authors in \cite{49}–\cite{51} discussed technical approaches to achieve maritime communications through collaborative heterogeneous wireless networks, formed by terrestrial networks, satellite networks, and other types of wireless networks.

The route of the development of MCNs is depicted in Figure 3. According to the network architecture, MCNs can be categorized into satellite-based, shore-based, island-based, vessel-based, and air-based networks, motivated by various communications and networking technologies. They will be discussed in the following.

A. Satellite-based Maritime Communications

Inmarsat is an international geostationary earth orbit (GEO) satellite communication system. It aims to provide worldwide voice and data communications services for various applications, such as ocean transport, air traffic control, and emergency rescue \cite{52}. The first generation of Inmarsat systems (Inmarsat-1) was put into use in 1982. The system is composed of several satellites and transponders rented from other companies and organizations, mainly providing analog voice,
fax, and low-speed data services. The second-generation system (Inmarsat-2) was put into use in 1990. It has a total of four satellites, each of which is equipped with a single global beam, providing digital voice, fax, and low/medium-speed data services. The third-generation system (Inmarsat-3) was put into use in 1996. There are 5 satellites, and each satellite has 4-6 regional spot beams in addition to the global beam. Inmarsat-3 can support mobile packet data service (MPDS), with a capacity 8 times that of Inmarsat-2. The state-of-the-art Inmarsat-4 system consists of 3 satellites. Each satellite has a global beam, 19 regional beams, and around 200 narrow spot beams. Inmarsat-4 can provide Internet services with a peak rate of 492 kbps.

Iridium is an LEO satellite communication system providing voice and low-speed data services for users with satellite phones and pagers. The second generation of Iridium satellite constellations, Iridium Next, began to be deployed in 2017. It consists of 66 active satellites, 9 in-orbit spare satellites, and 6 on-ground spare satellites. At present, Iridium Next provides data services of up to 128 kbps to mobile terminals, and up to 1.5 Mbps to Iridium Pilot marine terminals. In the future, Iridium-5 system, also known as Global Xpress, aims to provide worldwide customers with downlink services of 50 Mbps and uplink services of 5 Mbps.

Tiantong-1 is China’s first mobile satellite communication system, which is also known as the Inmarsat in China. The system was launched into orbit in 2016, and put into commercial use in 2018. It mainly covers the Asia-Pacific region, including most of the Pacific Ocean and the Indian Ocean. It provides voice, short message, and low-speed data services, with a peak rate of 9.6 kbps.

The Shijian-13 communication satellite is China’s first high-throughput communication satellite. For the first time, this satellite uses the Ka-band multi-beam broadband communication system, and its total communication capacity is more than 20 Gbps, which is about 10 times higher than before. The satellite is designed with 26 user spot beams, covering nearly 200 kilometers of China’s offshore areas.

Another high-throughput satellite EchoStar-19 has a capacity of more than 200 Gbps and is equipped with 138 customer communications beams and 22 gateway beams. The satellite will provide users in North America with high-speed Internet services and some urgently needed relief. In addition, Ka-band based airborne broadband services will be available on the EchoStar-19 satellite.

The satellite-based communication systems have wide area coverage, and can provide low-speed or high-speed data services depending the narrowband or broadband access. However, satellite-based communications are greatly affected by climatic conditions and the marine environment, resulting in low reliability. Besides, the cost of ship-borne equipment and the communication charges are also very high. For example, the cost of installing ship-borne equipment for Inmarsat (Fleet 77) is approximately $28000, including the antenna, terminal, handset, manuals, SIM card and power supply, and the data service fee is $2.8 per minute.

**B. Shore-based Maritime Communications**

The NAVTEX system is a narrow-band system with data rates of 300 bps, providing direct-printing services for ships within 200 nautical miles offshore. It operates at the MF band, using the 518 kHz band to broadcast international information, and the 490 kHz band for local messages. The NAVTEX system delivers navigational messages, meteorological warnings and forecasts, and emergency information to enhance marine safety, but it cannot provide broadband communication services or obtain real-time information from users.

![Fig. 3. The developing route of MCNs.](image-url)
The PACTOR system is also a narrow-band system, which can provide text-only e-mail services with data rates of 10.5 kbps. It operates at the HF band, using frequencies between 1 MHz and 30 MHz [71]. The first generation of PACTOR systems (PACTOR-I) was built to provide a combination of direct-printing and packet radio services. Adaptive modulation methods and orthogonal frequency division multiplexing (OFDM) technologies were applied to PACTOR-II and PACTOR-III, respectively, in order to improve the spectral efficiency. The state-of-the-art PACTOR-IV system uses adaptive channel equalization, channel coding, and source compression techniques, and has proven to be suitable for channels with heavy multi-path propagation. Similar to NAVTEX, the PACTOR system still cannot provide real-time communication services due to large transmission delay [72].

With the development of wireless communications technologies, several broadband MCNs have been constructed. The world’s first offshore LTE network was jointly developed by Tampnet in Norway and Huawei in China. It covers the platforms, tankers, and floating production storage and offloading (FPSO) facilities from 20 km to 50 km offshore on the North Sea, providing voice and data services of 1 Mbps (uplink) and 2 Mbps (downlink). It also supports video surveillance data uploading and wireless trunking communication services [73].

Ericsson has also been working on connecting vessels at sea with shore-based BSs. It aims to enable maritime services that facilitate crew infotainment, cargo monitoring, and shipping route optimization. Ericsson and China Mobile has constructed a TD-LTE trial network for maritime coverage in Qingdao, China. The network operates at the 2.6 GHz band, covering areas up to 30 km offshore with a peak rate of 7 Mbps. It can provide broadcast services for offshore applications, such as maritime transportation and offshore fisheries [74].

The shore-based MCNs, as extension of terrestrial 4G/5G and beyond networks, can provide broadband communications services for offshore applications, such as multimedia file downloading and video surveillance data uploading. However, the shore-based MCNs have limited coverage compared with satellite networks, and the coverage performance depends largely on the geometrically available BS sites. Shore-based communications are suitable for maritime applications that are densely clustered in a small area and tolerate blind zones elsewhere.

C. Island-based Maritime Communications

For the remote islands on the sea, high-quality communication services can not only bring various kinds of information to the islanders, but also provide strong support for the timely communications and interconnection of border information. In 2015, the U.S. wireless provider Verizon Communications enhanced 4G LTE network coverage throughout the Rhode Island. It can provide the islanders and nearby vessels with web browsing and file downloading services [75]. In 2016, China Mobile set up a 4G BS on the Yongshu Reef, which is more than 1,400 kilometers from the mainland of China. By establishing satellite ground stations on the island, the signals from the island can be transmitted to the satellites, then to the ground stations on the mainland, and then to all parts of the country. The transmission rate has reached 10 Mbps on the island, and 15 Mbps of nearby ship-borne communication equipment. In 2017, China Telecom set up four 4G BSs on the Nansha Islands, which were connected to the mainland using underwater cables. The BSs provide coverage for the islands and reefs such as Yongshu Reef, Qibi Reef, Meiji Reef and nearby sea areas, enhancing broadband communication services [76].

The construction of island-based BSs further expands the coverage of coastal mobile signals. Island-based MCNs can support clear voice and video calls from the coast to the island, and provide high-quality communication services for the surrounding ships and fishermen. On the other hand, island-based BSs are more vulnerable to extreme climate events, such as typhoons and rainstorms.

D. Vessel-based Maritime Communications

The Japanese Ministry of Internal Affairs and Communications has developed a maritime mobile ad-hoc network (Maritime-MANET) to expand the coverage of shore/island-based MCNs via ship-to-ship communications. The network uses 27 MHz and 40 MHz frequency bands, covering areas up to 70 km offshore. However, the transmission rate is only 1.2 kbps, supporting narrowband communication services, such as the short message service (SMS) [77].

Singapore has launched the TRITON project, aiming to develop a wireless mesh network to expand the coverage area. In this network, each vessel, maritime beacon, or buoy serves as a mesh node, which can route traffic for other nearby nodes. The network operates at the 5.8 GHz band, covering areas up to 27 km away from the shore, with a coverage rate of 98.91%. It can provide broadband communication services of 6 Mbps for offshore applications, but cannot cover the high seas [46–48].

The vessel-based mesh or ad-hoc networks can provide broadband communication services for most vessels and platforms along the coast. However, the link stability of vessel-based MCNs is restricted by the frequent change of sea surface and marine weather conditions. Besides, the mesh architecture requires a high density of vessels, and each vessel needs to install expensive equipment. Therefore, more reliable network protocols and more cost-effective ship-borne terminals are required for vessel-based maritime communications.

E. Air-based Maritime Communications

The Internet.org project was launched by Facebook in 2013, aiming to provide free Internet access for users in remote areas, including marine users. The project utilizes UAVs at altitudes of 55–82 km to serve as aerial BSs and form a network via laser communications. Until now, Facebook has teamed up with a set of mobile operators and handset manufactures, and has found a number of sites for deploying UAVs to cover impoverished areas in Latin America, Asia and Africa [78].

The Loon project was initiated by Google in 2013, aiming to provide Internet access for users in the countryside and
remote areas. The project uses super-pressure balloons at an altitude of 20 km to build a communication network. The network operates at the 2.4/5.8 GHz band, and can provide communication services of 10 Mbps. Although the project has not entered the commercial stage, it has provided emergency communication services for several areas suffering from natural disasters [79].

The BLUECOM+ project also uses tethered balloons as routers to extend land-based communications to remote ocean areas. It exploits TV white spaces for long-range wireless communications, and uses multi-hop relaying techniques to extend the coverage. Simulation results have shown that the BLUECOM+ solution can cover the ocean areas up to 150 km from shore, providing broadband communication services of 3 Mbps [42]–[45].

In general, the air-based MCNs can cover a wider area than the vessel-based MCNs, as the BSs are lifted high above the ocean surface. On the other hand, aerial BSs, such as UAVs and balloons, are easily damaged by the severe weather. The air-based MCNs can provide remote users with high-rate and low-reliability communication services.

The main parameters of the existing MCNs are compared in Table 1. In terms of satellite communications, narrow-band satellites represented by maritime satellites mainly provide services such as telephone, telegraph and fax, and the communication rate is low. The newly launched high-throughput satellites enable broadband maritime coverage. However, the cost of ship-borne equipment is still very high. In addition to maritime satellites, shore & island-based BSs can be built to extend the maritime coverage of terrestrial 4G/5G networks. UAVs, high-end ships and offshore lighthouses can be exploited as well to serve as maritime BSs. The coverage performance of the MCN depends largely on the above-mentioned geographically available BS sites, and the transmission efficiency of a single BS is affected by maritime weather conditions, e.g., wave fluctuations, and the link stability is poorer compared with terrestrial scenarios. From the above, it is necessary to enhance the transmission efficiency in the complex and dynamical maritime environment, to extend the coverage by taking the advantages and overcoming the shortcomings of different coverage methods, and to develop service-oriented transmission and coverage techniques to meet the unique service requirements from maritime applications.

IV. ENHANCING MARITIME TRANSMISSION EFFICIENCY

Compared with the terrestrial environment, the atmosphere over the sea surface is unevenly distributed due to seawater evaporation. The electromagnetic propagation environment is susceptible to sea surface conditions (tidal waves, etc.) and atmospheric conditions (temperature, humidity, wind speed, etc.), as depicted in Figure 4. In addition, the height and angle of ship-borne antennas are rapidly changing with the fluctuation of the sea surface. The maritime channel fading is particularly sensitive to parameters such as antenna height and angle, which may cause frequent link interruption. These complex time-varying factors lower the transmission efficiency in maritime scenarios.

To enhance the transmission efficiency, it is necessary to understand and make full use of the characteristics of the wireless propagation environments over sea. Compared with terrestrial scenarios, the electromagnetic propagation environment is affected by various weather conditions, such as sea surface conditions and atmospheric conditions, presenting unique maritime channel characteristics. Therefore, the measurement and modeling of the maritime channel is very important for the analysis and design of MCNs [16]. On the other hand, more advanced resource allocation schemes, such as dynamical beamforming and user scheduling techniques, should be studied to utilize the dynamic changes of maritime channels. In addition, evaporation ducts may exist due to uneven atmospheric humidity above the sea surface, which can trap the signal inside and greatly reduce the transmission loss. It is possible to exploit the evaporation duct effect to improve the transmission efficiency, especially for remote transmissions.

A. Characteristics and Models of Maritime Channels

Various channel measurements and modeling projects have been conducted to analyze the impact of system parameters (frequency, antenna height, etc.) and maritime environments (sea state, weather conditions, etc.) on the maritime channel fading [80]–[110]. According to the rate of variation of these parameters over time, maritime channel fading can be classified into large-scale fading and small-scale fading. The large-scale fading varies slowly on the order of the users’ location change. The small-scale fading refers to the rapid fluctuations in signal amplitude, phase, or multi-path delay over a signal wavelength.

For the large-scale fading characteristics of maritime channels, Y. Bai et al. studied the influence of ground curvature on the signal propagation characteristics of the maritime environment, and made the link budget for Wideband Code Division Multiple Access (WCDMA) systems [80]. K. Yang et al. studied the adaptability of several terrestrial channel models to the maritime environment in the 2 GHz band and found that the model adopted by the International Telecommunication Union Radiocommunication Group (ITU-R) agrees well with the measurement results [81]. However, the ITU-R model introduces simple corrections to different terrains, and therefore does not truly reflect the complex maritime variations such as sea reflections and evaporation ducts.

Considering the impacts of sea surface reflections, some recent works [82]–[85] studied the two-ray channel model and
proposed several modified models. Among them, Y. Zhao et al. considered factors such as sea surface reflection and antenna height, and proposed a two-ray model suitable for maritime channels [82]. The model assumes that the maritime channel mainly consists of a direct path and a reflection path, and its path loss can be expressed as

\[
L_{2\text{-ray}} = -10\log_{10} \left\{ \left( \frac{\lambda}{4\pi d} \right)^2 \left[ 2 \sin \left( \frac{2\pi H_1 H_2}{\lambda d} \right) \right]^2 \right\}
\]

where \( \lambda \) is the carrier wavelength, \( d \) is the distance between the transmitting antenna and the receiving antenna, \( H_1 \) and \( H_2 \) represent the antenna heights of the transmitter and the receiver, respectively.

Besides, J. C. Reyes-Guerrero et al. measured the maritime channel under non-line-of-sight (NLOS) scenarios and proposed a simplified two-path model by using a geometrical approximation method. Compared with the free-space model and the two-ray model, this model is only appropriate for transmission over short distances [83]. N. Mehrnia et al. introduced the index correction coefficient in the two-ray model formula and obtained better channel prediction in the 5 GHz band [84]. Jae-Hyun Lee et al. studied large-scale fading characteristics and small-scale fading characteristics in the 2.4 GHz band, and found that the two-ray model considering the wave height of waves is more consistent with the experimental data in general [83]. This modified two-ray model can achieve good fitting effects under certain scenarios, but is only applicable to offshore areas within a short distance.

In the marine atmosphere, special atmospheric refractive index structures easily form evaporation ducts, so that the electromagnetic wave has an extra scattering energy gain, enabling it to propagate to more distant areas. The evaporation duct effect is necessary for communications at longer distances. Y. H. Lee et al. measured the near-shore channel under the line-of-sight (LOS) scenario. The analysis shows that, when the distance between the transmitter and receiver exceeds a certain threshold (relative to the heights of the transmitting and receiving antennas), the presence of the evaporation duct will affect the path loss. In addition, Y. H. Lee et al. proposed the three-ray path loss model, which is closely related to the heights of the evaporation duct and the transmitting and receiving antennas [86]. The height of the evaporation duct can be estimated using the Paulus-Jeske empirical model (PJ model). A. Coker et al. simulated and analyzed the effect of evaporation duct height on signal attenuation and diversity [87]. More recently in [83], the authors proposed a way to estimate the evaporation duct height using a novel refraction profile model. Under proper sea conditions, the 3-ray model considering the evaporation duct has obvious advantages over the 2-ray model, and its path loss can be expressed as

\[
L_{3\text{-ray}} = -10\log_{10} \left\{ \left( \frac{\lambda}{4\pi d} \right)^2 \left[ 2 \sin \left( \frac{2\pi H_1 H_2}{\lambda d} \right) \right]^2 \right\}, \quad d < d_{\text{break}}
\]

\[
-10\log_{10} \left\{ \left( \frac{\lambda}{4\pi d} \right)^2 \left[ 2 \sin \left( \frac{2\pi H_1 H_2}{\lambda d} \right) \right]^2 \right\}, \quad d > d_{\text{break}}
\]

where \( \Delta = 2 \sin \left( \frac{2\pi H_1 H_2}{\lambda d} \right) \sin \left( \frac{2\pi (H_e - H_1) (H_e - H_2)}{\lambda d} \right), \) \( d_{\text{break}} = \frac{4H_1 H_2}{\lambda}, \) and \( H_e \) denotes the height of evaporation duct layer.

In addition to path loss, the maritime channel model needs to consider small-scale fading caused by sea-level fluctuations and atmospheric scattering. X. Hu et al. pointed out that multi-path reflection on the sea surface can be divided into coherent specular reflection and non-coherent diffuse reflection, and the concept of effective reflection area was proposed [89]. M. Dong et al. used the Rayleigh roughness decision criterion to prove that the diffuse reflection from the sea surface is negligible when the sea level is lower than 6 and the grazing angle is less than 5 degrees [90]. K. Haspert et al. proposed a theoretical approximation modeling method that can be applied to multi-path channels containing specular and diffuse reflection components [91]. K. Yang et al. measured the channel between the transmitting antenna on the far sea and the receiving antenna on the shore, and analyzed the important influence of the antenna position on signal propagation based on the received signal level (RSL) and the power delay profile (PDP) [92]. J. Lee et al. analyzed the probability density function (PDF) of the small-scale fading, and pointed out that the PDF is more approximate to the Rice distribution than the Nakagami-m distribution and the Rayleigh distribution [93]. K. Yang et al. analyzed the Doppler shift [94]. F. Huang et al. considered the smooth sea surface and the rough sea surface. The impulse response model of a multi-path channel, composed of the direct path, reflected paths, and scattering paths, was obtained. The model is suitable for different carrier frequencies, transmission distances, and sea states [95]. More recently in [96], the authors performed ship-to-shore propagation measurements at the 1.39 GHz band and the 4.5 GHz band, and proposed a model to capture the behavior of small-scale fading at different frequency bands.
is affected by both shadowing effect and multipath effect. When the weather conditions are poor, the signal is transmitted through the channel. The signal received by the terminal includes multi-path and direct components. At this time, the received signal envelope follows the Rice distribution, and the small-scale fading model of the maritime channel can be described by the Suzuki model, i.e.,

\[
p(a)=\int_{0}^{\infty} a \exp\left(-\frac{a^2}{2\sigma^2}\right) \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\ln \sigma - \mu)^2}{2\sigma^2}\right) d\sigma \quad (3)
\]

where \( \sigma \) is the standard deviation of each Gaussian component, \( \mu \) and \( \sigma_l \) are the mean and standard deviations of signals that follow the Log-normal distribution, respectively. For maritime satellite channels, the authors in [103] measured the channel fading with different antenna types and elevation angles, and compared the performance of several modulation schemes. The authors in [104] and [105] analyzed the characteristics of rain fading on the Ka-band using the statistics extracted from satellite-to-beacon propagation measurements.

The parameters of representative maritime channel measurements and modeling projects are listed in Table II. The maritime channel model is not only related to parameters such as signal frequency, transmission distance, antenna height and moving speed, but also affected by oceanic weather and sea surface fluctuations [106]–[109]. The above studies have considered one or two specific factors, and measured the relevant received signal strengths under specific experimental setups and marine environments, but have not considered the impact of all influencing factors on the channel fading. On the other hand, the transmission efficiency in MCNs is envisioned to be enhanced by using some most promising technologies in 5G systems, such as massive multiple-input multiple-output (MIMO) technologies, millimeter wave (mmWave) communications, and vehicle-to-vehicle (V2V) communications [111]. Until now, plenty of massive MIMO channel models [112]–[115], mmWave channel models [116][117], V2V channel models [118][119], and channel models for high-mobility systems [120]–[123] have been proposed, and a general 5G channel model can be used for simulating the above channels [124]. However, these models are mostly based on the channel measurement results in terrestrial scenarios, and whether they are suited for the environment-sensitive maritime channels still needs to be explored [23]. Therefore, it is necessary to carry out further measurements and modeling studies on maritime channels.

B. Reducing Transmission Loss: Exploiting Evaporation Duct for Remote Transmissions

The atmospheric refractive index over sea surface varies with the maritime environment. Electromagnetic waves have different propagation paths depending on the rate at which the refractive index changes with height. When the rate meets certain conditions, atmospheric ducts will be formed, and signals will be trapped therein, as depicted in Figure 6 [125]. Atmospheric ducts can be utilized to improve transmission efficiency, as the propagation loss in the duct layer is much smaller than that in free space [126].

Three kinds of atmospheric ducts often appear over sea surface, namely surface duct, elevated duct, and evaporation duct. The evaporation duct, formed by a large amount of seawater evaporation about 0–40 m above sea level, is the most common kind of atmospheric ducts, and only occurs...
in the oceanic atmosphere \[125\]. Using the evaporation duct, several radio links have been set up for beyond-LOS maritime communications, such as the 78-km link from the Australian mainland to the Great Barrier Reef \[126\], and the 100-km link between Malaysian shores \[127\]-\[128\].

It should be noted that the height of evaporation duct layer depends on various environmental factors, such as air-sea temperature differences, humidity, air pressure, wind speed, and wave height \[129\]. Although the P-J formulation can be used to calculate the duct height, it may lose the prediction accuracy due to its sensitivity to the weather information. The utilization of evaporation duct for maritime communications is still in the primary stage. To promote the development of MCNs, more meteorological instruments are needed to collect the vertical weather information, and more accurate models are required to predict the channel state information (CSI).

### C. Improving Resource Utilization: Resource Management and Allocation Schemes

The transmission efficiency of MCNs is subject to the channel environment. Therefore, more advanced resource allocation schemes, such as dynamical beamforming and user scheduling techniques, should be studied to utilize the dynamic changes of maritime channels. For random and rapidly changing wireless channels, traditional resource allocation and utilization methods based on service statistics and characteristics are inefficient, which results in a significant decrease in the overall performance of the network. In order to deal with the dynamic changes of maritime channels with sea surface and weather conditions, it is necessary to fully exploit the characteristics of the MCN.

The authors in \[130\] exploited vertically-spaced multiple antennas at the receiver side, and proposed a frequency and time synchronization and scheduling scheme to overcome deep fading, utilizing the two-path characteristic of maritime channels. The authors in \[131\] proposed a service-oriented framework for the management of MCNs, and developed three policy-based routing schemes using the framework. In addition to the above works, WiMAX and delay-tolerant networking (DTN) technologies have been widely discussed for maritime communications \[132\]. The authors in \[133\] used the WiMAX-based mesh technology for ship-to-ship communications with DTN features, and compared the performance of different routing schemes. The authors in \[134\] studied the scheduling of data traffic tasks to optimize the network throughput and energy sustainability. More recently in \[135\], the authors proposed a joint backhaul and access link resource management scheme for the maritime mesh network to maximize the network capacity.

Specifically, in contrast to terrestrial networks, user behavior characteristics are useful in MCNs to improve its transmission efficiency, since most marine users, such as passenger ships and cargo vessels, follow specific shipping lanes \[136\]-\[138\]. The authors in \[139\] constructed a model of ship encounter probability, and used the model to analyze the data delivery ratio. The authors in \[140\] proposed an architecture of delay-tolerant MCNs where the AIS is integrated to obtain the trip-related data of ships, and optimized the routing performance utilizing ship contact opportunities. In \[141\] and \[142\], the authors proposed energy-and-content-aware scheduling algorithms for video uploading in MCNs based on the deterministic network topology and the ship route traces, respectively.

The studies in Section IV.A have suggested that maritime channels consist of only a few strong propagation paths due to the limited number of scatterers, making the large-scale channel fading more dominant. Thus, it is a promising way to allocate resources with the large-scale CSI, which can be conveniently acquired from the location information in the MCN \[143\]. Previous studies have explored the performance gain achieved by power allocation \[144\] and user scheduling.
techniques with only large-scale CSI, and suggested that coordinated transmissions with large-scale CSI have a bright prospect in practical MIMO or distributed MIMO systems to improve the spectral efficiency and energy efficiency \cite{146}.

Since the electromagnetic propagation environment over the sea is susceptible to sea surface conditions and atmospheric conditions, the future MCNs should be able to perceive environmental information, such as the sea level, temperature, humidity, wind speed, etc., to make more accurate prediction of the CSI, and intelligently adopt more efficient transmission techniques to utilize the dynamic changes of maritime channels.

V. INCREASING BROADBAND COVERAGE

Satellite communication systems can cover a wide area over sea, but most of them only provide narrowband communication services. For example, the communication rates of Iridium and Globalstar are 4.8 kbps and 9 kbps, respectively \cite{147}\cite{148}. The newly launched high-throughput satellites, such as EchoStar-19 and Inmarsat-5, have enabled broadband maritime coverage. However, the cost of ship-borne equipment is still very high \cite{29}. Data from the AIS show that there are nearly 80,000 ships sailing simultaneously around the world, while less than 25,000 of them are high-end ships (with a load of more than 10,000 tons) that may afford the ship-borne equipment for high-throughput satellite communications.

In addition to maritime satellites, shore & island-based BSs can be built to extend the maritime coverage of terrestrial 4G/5G networks. UAVs, high-end ships and offshore lighthouses can be exploited as well to serve as maritime BSs. The coverage performance of the MCN depends largely on the above-mentioned geometrically available BS sites. Due to the limited onshore BS sites, and the high mobility of the ship-borne BSs, aerial BSs and users, the topology of the MCN is highly irregular. There always exist blind zones within the coverage area. Besides, when the BS covers the remote users with high power, it will generate strong co-channel interference to the nearby users served by the neighboring BSs.

Considering these problems, the MCN has to make full use of the available BSs, including onshore BSs, ship-borne BSs, aerial BSs and satellites, as depicted in Figure 7. By using multi-hop wireless networking and satellite-terrestrial integration technologies, the BSs can work cooperatively to increase broadband coverage. Besides, more advanced transmission techniques, such as dynamic beamforming and microwave scattering, are needed to reduce the signal attenuation and extend the coverage of a single BS.

A. Building and Exploiting Offshore BSs: Multi-hop Wireless Networking Techniques

To achieve wider coverage of MCNs, the authors in \cite{149} and \cite{150} proposed ad-hoc-based networks named Maritime-MANET and Nautical Ad-hoc Network (NANET), respectively. Similarly, the authors in \cite{133} proposed a WiMAX-based mesh network to provide delay-tolerant maritime communication services. To improve the efficiency of ship-to-ship communications in the above MCNs, multiple directional antennas were used in \cite{149}, virtual MIMO technologies were introduced in \cite{151}, two relay schemes were designed in \cite{152} and \cite{153}, a novel handover protocol was proposed in \cite{154}, a distributed adaptive time slot allocation scheme was proposed in \cite{155}, and a cognition-enhanced mesh medium access control (MAC) protocol was proposed in \cite{156}. Further, the authors in \cite{157} proposed the framework of an integrated MCN consisting of NANETs, terrestrial cellular networks, and satellite networks, in order to meet the requirements of various services.

Various routing methods and protocols have been proposed for delay-tolerant ad-hoc networks \cite{158}\cite{159}, such as epidemic routing \cite{160}, probabilistic routing \cite{161}, spray and wait \cite{162}, schemes based on network coding \cite{163}\cite{164}, Optimized Link State Routing (OLSR) \cite{165}, Ad Hoc On Demand Distance Vector (AODV) Routing \cite{166}\cite{168}, and Ad Hoc On Demand Multipath Distance Vector (AOMDV) \cite{169}. However, these schemes showed poor performance when applied to maritime communications, such as large delivery delay and low delivery ratio, due to the lower user density compared with terrestrial scenarios \cite{170}. Therefore, routing protocols dedicated to maritime mesh networks are required \cite{171}\cite{173}.

In \cite{174}, the authors proposed an opportunistic routing scheme for delay-tolerant MCNs based on lane intersecting opportunities. In \cite{141}, the authors proposed three offline scheduling algorithms for video uploading in MCNs based on the deterministic network topology. In \cite{175}, the authors proposed a route maintenance method for maritime sensor networks based on ring broadcast mechanism. These studies utilized the predictability and stability of user movement, but did not take the full advantage of the physical characteristics of maritime channels. The features and applicable scenarios of representative routing protocols for maritime communications are listed in Table III. It is worth mentioning that the height and angle of the ship-borne antenna are rapidly changing with the fluctuation of the sea surface. Besides, maritime channel fading is sensitive to antenna height and angle \cite{102}. To solve this problem, we need to establish a sensitivity model for the received signal strength, the height of the ship-borne antennas, and the sea surface fluctuation intensity, and based on this,
optimize the routing algorithm to reduce the packet loss rate and network delay.

Besides, marine traffic fluctuates over time, resulting in changes in BS loading. Using BS switching, the MCN can shut down some low-loaded BSs when the traffic is low, so as to not only support current user communication requirements, but also save energy and reduce interference to neighboring users. At present, the switch selection methods applicable to terrestrial fixed BSs are based on BS’s performance indicators such as coverage, cell load, and neighboring cell interference, to provide a BS deployment scheme and a switching method. However, unlike terrestrial BSs, a ship-borne BS has the following two characteristics: First, the power resources are limited, so it is more necessary to save energy. Second, the onboard BS has high mobility, so if the switch selection method of the ground fixed BS is applied to maritime communications, either the BS switch operation is too frequent or the BS switch configuration for a period of time does not meet the user’s needs. Therefore, the existing BS switch selection method does not apply to the onboard BS. Switch selection methods of ship-borne BSs suitable for maritime communications need to be investigated. For example, the authors in [178] proposed a ship-borne BS sleeping control and power allocation scheme for the MCN based on the sailing route to enhance the robustness of dynamic coverage.

In addition to ship-borne BSs, UAVs can be exploited as well to construct aerial maritime BSs, and serve as relay nodes to widen the coverage of the MCN. In [179], the authors focused on the reliability, and optimized the altitude of the UAV as a relaying station. In [180], the authors considered UAV-aided data collection for the maritime IoT, and optimized the transmit power and duration of all devices to maximize the data collection efficiency. Due to the agile maneuverability, UAVs are considered as effective tools to achieve dynamic and flexible coverage of the MCN.

B. Utilizing High-throughput Satellites: Multi-spot Beams and Satellite-terrestrial Cooperation

Besides constructing a mesh network using ship-borne BSs and UAVs, satellites can also be exploited to extend the coverage of MCNs. The utilization of satellite communications for maritime coverage has been widely reported in the literature [181]–[200]. Although satellite communications have a wide coverage, they are still seriously restricted by their high latency and low data rate. In order to enhance broadband coverage of maritime satellites, spot beam and frequency reuse technologies have been studied. Since a narrower beam width leads to a higher antenna gain, the use of spot beam technologies can increase the spectral efficiency, and allow maritime users to use smaller satellite terminals [181]–[183]. Further, the use of multi-spot beams allows beams that are far apart to reuse frequency. Frequency reuse is an effective way to improve spectral efficiency, but it may bring about strong inter-beam interference due to the non-zero side lobes [184]. Therefore, side lobe suppression technologies are required for the use of multi-spot beams, and there is a trade-off between the number of spot beams and the distance between frequency-reuse beams [185]–[186]. It should be noted that in the scenario of maritime communications, the density of vessels/platforms/islands is low, while the users are clustered thereon. Therefore, using multi-spot beams is an effective way to enhance broadband coverage for MCNs [187]–[188].

Since terrestrial communications networks have generally high capacity with limited coverage, while satellites can provide wider coverage with lower data rate, an integrated satellite-terrestrial network (ISTN) is a promising way to enable seamless broadband coverage, taking the advantages of both networks [189]. Up to now, a number of papers have reviewed ISTNs from different perspectives [24] presented a review of several important issues for ISTNs, such as network design and optimization. [190] pointed out some research directions for ISTNs, focusing on the network layer and the transport layer. [191] made a survey on the QoS performance for the ISTN. [192] described an ISTN for multimedia broadcasting services and the required resource management strategies. [193] investigated the problem of cooperative transmission in future ISTNs. [194] presented the concept and key issues of cognitive ISTNs. Further, the authors in [195] considered a cognitive ISTN where the terrestrial system shares resources with the satellite network under the constraint of interference temperature, and compared the outage performance of different secondary transmission schemes. In [196], the authors considered an ISTN where cognitive relay stations are set to forward the received signals from satellites, and proposed a power allocation scheme to maximize the achievable rate. In [197], the authors considered the integration of UAVs into the satellite network, and proposed a power allocation algorithm to improve user fairness.

Specifically, for maritime communications, the authors in [198] proposed intelligent middleware and link specific protocols for the coordination of maritime mesh networks and satellite communication networks, as depicted in Figure 8. The authors in [199] considered a hybrid Satellite-MANET consisting of GEO, MEO, LEO satellite systems and terrestrial MANET. The authors analyzed the coverage radii distributions for full connection, and proposed a multi-hop routing protocol to minimize the end-to-end propagation delay. The authors in [200] proposed an OceanNet Backhaul Link Selection (OBLs) algorithm to select the optimal backhaul links with the best signal to noise ratio (SNR). Further, the authors implemented the proposed algorithm in a hardware test-bed modeling the maritime network topology.

C. Reducing Signal Attenuation: Phased-array Antennas and Beam Scheduling Techniques

Directional beams are commonly used to widen the coverage area. The concept of beamforming has been introduced in 5G, where the beamforming vectors are complexly calculated based on the MIMO CSI [201]. In the scenario of maritime communications, the density of vessels is low while the users are clustered in a small area (ship/platform), which makes it easy to determine the beam directions according to the users’ geographical location information. Thus, it is also a convenient way for MCNs to use phased array antennas with
TABLE III
ROUTING PROTOCOLS FOR MARITIME COMMUNICATIONS.

| Reference | Protocol | Feature | Applicable Scenario |
|-----------|----------|---------|---------------------|
| [157]    | Routing Application for Parallel Computation of Discharge (RAPID) | Replica-based (flooding) | Ships in low density |
| [159]    | Epidemic Routing (ER) | Replica-based (flooding) | Ships in low density |
| [161]    | Probabilistic Routing (PR) | Replica-based (flooding) | Ships in low density |
| [162]    | Spray and Wait (SaW) | Replica-based (flooding) | Ships in low density |
| [163]    | Estimation Based Erasure Coding (EBEC) | Coding based | Ships in low density |
| [164]    | Hybrid Erasure coding (HEC) | Coding based | Ships in low density |
| [165]    | Optimized Link State Routing (OLSR) | Regular | Ships in good density |
| [166]    | Ad Hoc On Demand Distance Vector (AODV) | Regular | Ships in good density |
| [169]    | Ad Hoc On Demand Multi-path Distance Vector (AOMDV) | Regular | Ships in good density |
| [172]    | Lane-Based Opportunistic Routing (LampPost) | Knowledge based | Ships in low density |
| [175]    | Geographical Routing (GR) | Knowledge based | Ships in low density |
| [177]    | Gradient Routing Based on Link Metrics (GR-LM) | Knowledge based | Ships in low density |

Fig. 8. Using intelligent middleware for satellite-terrestrial cooperation [198].

analogue beamforming to reduce the cost. The use of phased array antennas can effectively increase the coverage of MCNs with a lower cost based on the existing LTE networks [202], as the directions of antennas can be conveniently determined according to the location of users.

The users’ location information can be accessed by the AIS. The BS receives the location information and steers the antennas to point to the selected directions [203]. It should be noted that directional beams can point to a narrower range of directions than omni-directional beams to decrease the signal attenuation, and the beams need to be dynamically scheduled, for higher throughput or wider coverage [204–206].

D. Exploiting Microwave Scattering for Over-the-horizon Coverage of Islands/Platforms

The earth’s atmosphere is generally divided into the ionosphere, the stratosphere, and the troposphere. The troposphere is the atmosphere from earth surface to an average altitude of 10–12 km. The turbulence and the inhomogeneous medium in the troposphere can scatter incident microwaves forward and earthward, realizing over-the-horizon communications. Microwave scattering communications have the advantages of long communication distance, large capacity, high security, and high flexibility. Therefore, microwave scattering is very suitable for providing communication services for users in environmentally harsh areas, such as mountains, deserts, and oceans [207–209].

The number of scatterers in the troposphere over the oceans is much larger than that in the troposphere over the ground, due to more frequent atmospheric flows. Thus, the transmission distance using microwave scattering in maritime communications is believed to be larger than that in terrestrial communications [210]. Until now, a great many experimental links have been set up for over-the-horizon maritime communications using microwave frequency band, such as the 5.8 GHz band [207] and the 2.2 GHz band [209].

It should be noted that the fading of scattering channels is deeper than the channel fading within LOS. High-power microwave antennas or large-scale antenna arrays are usually needed to compensate for the transmission loss. Therefore, microwave scattering communications are still not cost-effective, and are mainly used for the coverage of islands, warships, and drilling platforms [212].

E. Interference Alleviation for Irregular Network Topology

Due to the limited spectrum resources, some systems and beams of the MCN have to be frequency-multiplexed and the interference model is complicated. The traditional methods often deal with the inter-system interference and intra-system interference independently. However, the maritime communication network presents an irregular topology structure, and the coupling between the systems and the intra-system interference is stronger [213–215]. To solve this problem, it is envisioned to comprehensively schedule the beam resources between the satellite and the terrestrial network, study the optimal beam design method, and suppress inter-beam interference. At the same time, in order to reduce the complexity, the centralized processing is converted to distributed processing, based on the probability map model and message passing algorithms to explore low-complex multi-user joint precoding techniques. In [184], the authors investigated the impacts of diffracted waves from the structures of a ship on the received signal levels for aiming and neighboring satellites in maritime satellite communications, and found a relationship between the clearance angles and interferences. In [185], the authors focused on the interference between the mobile satellite service and the fixed service in a maritime environment in the Ku band, and analyzed some important parameters, such as the mobile earth station’s transmit power, antenna gain, speed, and the propagation environment. More recently, the authors in [216] and [217] analyzed the co-channel interference from maritime mobile earth station to 5G mobile service, and
suggested that a separate distance should be set to guarantee the quality of service (QoS) for 5G outdoor environments.

Due to the long distance covered by the sea surface, the propagation path needs to take into account the influence of the curvature of the earth. For sea surface coverage, the wireless signal travels vary far due to the small loss of radio wave transmission. At this point, the influence of the curvature of the earth on the sea surface must be considered, and the sea surface cannot be regarded as a plane. Therefore, the height of the antenna has a direct relationship with the coverage distance [218][219]. If the antenna height is too low, it will reduce the coverage of the BS. If the antenna height is too high, it will cause pilot contamination between neighboring cells. Therefore, the antenna height must be carefully planned for maritime communications.

On the other hand, when the BS covers the remote users with high power, it will generate strong interference to the close-range users served by the neighboring BSs, that is, the near-far effect. The processing of interference depends on the acquisition and estimation of CSI, but the pilot transmitted by the close-range user also generates strong interference to the pilot transmitted by the remote user, resulting in inaccurate channel estimation. Aiming at this problem, the pilots should be carefully designed [220].

Up to now, several key technologies to extend the coverage of MCNs, such as multi-hop wireless networking, satellite-terrestrial cooperation, microwave scattering, and dynamic beam scheduling, have been studied. In order to give full play to the advantages of the above-mentioned means of maritime coverage and overcome their shortcomings, a heterogeneous network can be formed by the coordination of maritime satellites, shore & island-based BSs, ship-borne BSs and UAVs. Besides, it is essential to intelligently configure the network, and effectively allocate spectrum and power resources based on the characteristics of different users’ service requirements [221]–[223].

VI. PROVIDING SPECIFIC MARITIME SERVICES

Taking a bird’s-eye view of the sea, one will find various kinds of marine users requiring communication services, as depicted in Figure 9. For all sailing vessels, navigational and operational communication services are required for safe navigation. For passengers, crew, fishermen and offshore workers, web browsing and multi-media downloading services are needed for their entertainment. The beacons are deployed to collect and upload meteorological and hydrological information, and platforms for oil exploitation require real-time operational data services. Particularly, when a marine accident happens, real-time video communications will be of great help for the wreckers to carry out rescue.

It is worth mentioning that the above-mentioned services have specific requirements for bandwidth, latency and reliability. For example, the data services for maritime rescue and operation of oil platforms have a critical demand of real-time latency and high reliability. The multimedia downloading and data gathering services, however, usually have a higher demand of bandwidth, with tolerance for high latency. Specifically, as for the spatial distribution of maritime services, we note that the density of vessels is low, while the users (passengers/crew/fishermen/offshore workers) are clustered in a small area (ship/platform). Therefore, the passenger/crew infotainment services are sparsely distributed on the sea, but densely clustered in each vessel.

In view of this, the next part of this section introduces the existing and potential schemes to provide the maritime-specific services. In addition to the intelligent navigational communication services required by all vessels, the clustered distribution services, delay/reliability-sensitive maritime services, as well as delay-tolerant maritime services will be discussed.

A. Intelligent Navigational Communication Services

In order to achieve safe navigation, promote scientific supervision, and improve shipping efficiency, the sailing ships need to be provided with real-time and accurate maritime traffic information in the fastest and most efficient way. In [224], the authors considered the feasibility of utilizing illuminating signals sent by Inmarsat for maritime surveillance and navigation, especially for marine obstacle avoidance. In [225], the authors introduced the utilization of satellite-based AIS receivers to extend traffic monitoring zones to open seas, as well as the challenges of message collision in high traffic zones. More recently, the authors in [226] proposed a parallel signal processing architecture and algorithms for satellite-based AIS to cope with the message collision in dense maritime zones, and reduce the downlink power, bandwidth, and latency. Currently, an intelligent maritime transportation network is generally formed by making full use of the Geographic Information System (GIS), the Global Positioning System (GPS), remote sensing (RS), digital earth, digital ocean, and other technologies [227]–[232].

B. Passenger/Crew Infotainment: Clustered Distribution Services

Different from the terrestrial scenario, where users are scattered on the land, in the MCN, the density of vessels is low, while the users (passengers/crew/fishermen/offshore workers) are clustered in a small area (ship/platform) [233]. Therefore, the passenger/crew infotainment services are sparsely distributed on the sea, but densely clustered in each vessel. To provide such kind of maritime-specific services, phased array antennas and beamforming techniques can be used. The direction of beams can be controlled according to the location of vessels, which can be obtained from the AIS [234]. In [223], the authors proposed a user-centric communication structure and an antenna selection scheme based on distributed antennas. In [206], the authors proposed a location-aware dynamic beam scheduling scheme to provide users in each ship with guaranteed QoS, and reach a compromise between the throughput and fairness among different ships.

C. Mission-critical Services: Low Latency and High Reliability

When a marine accident occurs, real-time and high-reliability communication services are required for maritime...
Fig. 9. Maritime-specific communication services and their features.

search and rescue. The emergency communication systems based on UAVs and low-orbit satellites can realize real-time transmissions of voice, image, video, etc., and help improve the communication security level in the remote area. In addition, underwater emergency communications can also provide communication and location services for underwater rescue, wreck positioning, as well as search and salvage [235].

For ship-to-ship communications between the rescue team and the accident ship, it is worth mentioning that the height and angle of the ship-borne antennas are rapidly changing with the fluctuation of the sea surface. The fading of maritime channels is particularly sensitive to parameters such as antenna height and angle, which may cause frequent link interruption. To cope with this challenge, antenna switching techniques have been proposed in [46] and [236]. When the rocking angle of a ship is more than a threshold, antenna switching will be triggered to improve link stability and packet delivery ratio.

D. Multimedia Downloading and Data Gathering: Delay-tolerant Services

The downloading of multi-media and the uploading of hydro-meteorological information require broadband communications and high latency tolerance [237]. In order to provide this kind of delay-tolerant services, several resource scheduling methods for maritime communications have been proposed. In [174], an opportunistic routing scheme for delay-tolerant MCNs based on lane intersecting opportunities was proposed. In [141], three offline scheduling algorithms for video uploading in MCNs based on the deterministic network topology were proposed. These studies utilized the predictability and stability of marine users’ movement [238]. For future work, it is promising to explore the mobile law of offshore users, expand the scope of resource scheduling in the time domain, and explore resource scheduling frameworks and algorithms for wide-area mobile coverage. To this end, a new framework for joint optimization of services and BS transmission should be constructed. For example, a proxy is set up for each user, and the agent collects information such as the users’ location, shipping route, service demand, and link resource status of the BS, and combines the state of the sea environment. The resource scheduling is performed according to the estimation of user location and CSI, and then the data is pushed to the BSs, and transmitted to the users.

The maritime application scenarios are quite different, and the marine users’ service requirements are unique. Service-driven methods should be used to allocate resources, and user-centric transmissions should be used to implement rapid link-building services [239]. The information of resource conditions and service requirements could be exploited for flexible resource allocation for different services [240]. Through service-driven schemes, it is possible to comprehensively address the dynamic changes in the location and demand of marine users, as well as the wide range of maritime network coverage with severely limited resources.

VII. ARCHITECTURE AND FEATURES OF FUTURE MCNs

In addition to maritime satellites, shore & island-based BSs can be built to extend the maritime coverage of terrestrial 4G/5G networks. UAVs, high-end ships and offshore light-houses can be exploited as well to serve as maritime BSs. A heterogeneous network is useful by the coordination of spatial BSs and terrestrial BSs [241]. The terrestrial BSs mainly cover the offshore waters, and the satellites mainly cover the ocean areas. At the same time, the ship-borne BSs on the sea can be used as relay nodes to serve nearby vessels. To facilitate the use of the above-mentioned BSs, more advanced hardware needs to be developed, such as new antennas with higher directivity and lower complexity, radio frequency (RF) amplifiers with higher linearity and lower noise, as well as airborne and shipborne equipment with smaller volume and lower power consumption [242]–[245]. Besides, the future MCNs should enhance the transmission efficiency in the complex and varied maritime environment, extend the coverage by taking the advantages and overcoming the shortcomings of different coverage methods, and develop service-specific transmission and coverage techniques to meet the unique service requirements of marine users.
A. Requirements and Characteristics of Future MCNs

To improve transmission efficiency, the future MCNs should be able to perceive environmental information, such as the sea level, temperature, humidity, and wind speed, to make more accurate prediction of the CSI, and adopt more efficient transmission techniques to utilize the dynamic changes of maritime channels \([246]\). In addition, the future MCNs should be able to provide flexible services according to resource conditions and service requirements. Through service-driven networks, it is possible to comprehensively address the dynamic changes in the location and demand of marine users, thus providing dynamic and on-demand coverage with severely limited resources.

As depicted in Figure 10, the future MCN will adopt more flexible coverage modes and service patterns by utilizing the unique maritime channel and service characteristics. Specifically, the environmental information, positional information and service information can be collected by narrowband systems and exploited by the central processor (and BSs serving as edge processors \([247][248]\)) to design satellite-air-ground integrated transmission and coverage schemes. For example, a long-distance communication link can be dynamically established and digested, depending on whether the user is in an environment that satisfies the conditions under which the evaporating duct exists. When high-speed, high-reliability communication services are required for rescuing a vessel on fire, the nearby vessels and UAVs will gather together and work synergistically.

B. Exploiting the Knowledge Library for Intelligent MCNs

Due to the considerations in Section VII.A, it is recommended to establish a knowledge library for the future MCNs. The knowledge library is used to portray the complex signal propagation environment, network topology, and service characteristics, based on which the transmission efficiency and coverage performance can be greatly improved through intelligent optimization technologies. The knowledge library comes from both the internal information obtained during the communication process, such as the CSI, and the external auxiliary information, such as the maritime environment, network node position, and user behavior characteristics, as depicted in Figure 11. The external auxiliary information can be gathered by buoys, ship-borne sensors, etc., and uploaded to the central processor via narrowband systems. In the intelligent learning and optimization platform of the central processor, machine learning techniques are adopted to jointly process the internal and external information, and establish the knowledge library, including the hierarchical maritime channel model, the network topology evolution model, and the service characteristics model. The available BSs with extra storage capacity and computing power can be exploited to serve as edge processors, as well.

Utilizing the knowledge library, the intelligent learning and optimization platform will further perform transmission optimization, network management, and service scheduling for the MCN. For example, in terms of transmission optimization, with the meteorological and hydrological information gathered by maritime buoys and weather satellites, the intelligent learning and optimization platform will model the temporal-spatial distribution of maritime channels, and add it to the knowledge library. With the knowledge library, the MCN can predict the existence of deep-fading channels due to the 2-ray/3-ray propagation characteristic in maritime scenarios, and overcome the deep fading using diversity techniques. Besides, the MCN can estimate when and where an evaporation duct will exist, and further dynamically configure the network and allocate the resources for more efficient transmissions, as represented by the long-distance communication link in Figure 10.

In terms of network management, the BSs are statically deployed according to the statistical user distribution and link budget in traditional schemes, which fails to adapt to the dynamic network topology in the MCN. In contrast, with the knowledge of network node mobility, such as the shipping lane information obtained from the AIS, as well as the attitude of satellites and UAVs, the intelligent learning and optimization platform will construct the network topology evolution model for BS/user position prediction. Based on that, the network can be dynamically and intelligently configured for wider coverage, as represented by the irregularly-configured heterogeneous network in Figure 10.

In terms of service scheduling, based on user interest
and mission goals, the intelligent learning and optimization platform will establish a personalized service model, characterizing the distribution of service occurrence time, the length of service duration, and the service requirement. Based on the model in the knowledge library, the network can perform service forecasting, provide user-specific services, and dynamically adjust the allocation of resources in case of emergency communications, as represented by the vessel on fire in Figure 10. In general, statistical service models are applied for resource allocation, while a service-driven scheme will greatly improve the service capabilities of the MCN.

The utilization of the knowledge library will bring some new scientific problems based on the existing theories. Firstly, a hierarchical channel model can be built from the environmental and positional information in the knowledge library, and the CSI can be more precisely accessed as a priori knowledge through machine learning. The Shannon information theory focus on the stochastic channel, while the capacity with priori knowledge needs to be studied in depth. Secondly, based on the cellular network theory, the link and coverage performance are statically analyzed and the BSs are deployed accordingly. The knowledge library will enable dynamic networking according to the environmental/positional/service information. Therefore, the theoretical performance during the dynamic coverage process need to be studied, taking the temporal-spatial distribution of maritime environment into consideration. Thirdly, utilizing the user behavior and personalized service requirement/content models from the knowledge library, the MCN will be able to provide user-specific services. Statistical models are applied in the existing queuing theories, while a service-driven queuing model still needs to be explored. The evolution of these theories will contribute to bounding the network capacity and coverage with priori environmental/positional/service models, as well as inspiring more intelligent coverage and transmission schemes for the future satellite-air-ground integrated, environment-aware, and service-driven MCN.

VIII. Conclusions

This paper has provided a comprehensive review of hybrid satellite-terrestrial MCNs for the maritime IoT, including the ever-increasing demand for maritime communications, the state-of-the-art MCNs, the challenges of developing an efficient hybrid satellite-terrestrial MCN, and the key technologies for enhancing transmission efficiency, extending network coverage, and provisioning maritime-specific services. In particular, focusing on the unique characteristics of maritime communications compared with terrestrial and satellite communications, it has discussed the major challenges of MCNs from the perspectives of physical and geographical environments, as well as service requirements, and illustrated the corresponding solutions. It has also suggested developing an environment-aware, service-driven and satellite-air-ground integrated MCN, which should be smart enough to utilize the external auxiliary information, e.g., the sea state conditions. The architecture and features of future smart MCNs, as well as future research topics, have been outlined.

Fig. 11. Exploiting the knowledge library for intelligent coverage and transmission in the future MCN.

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